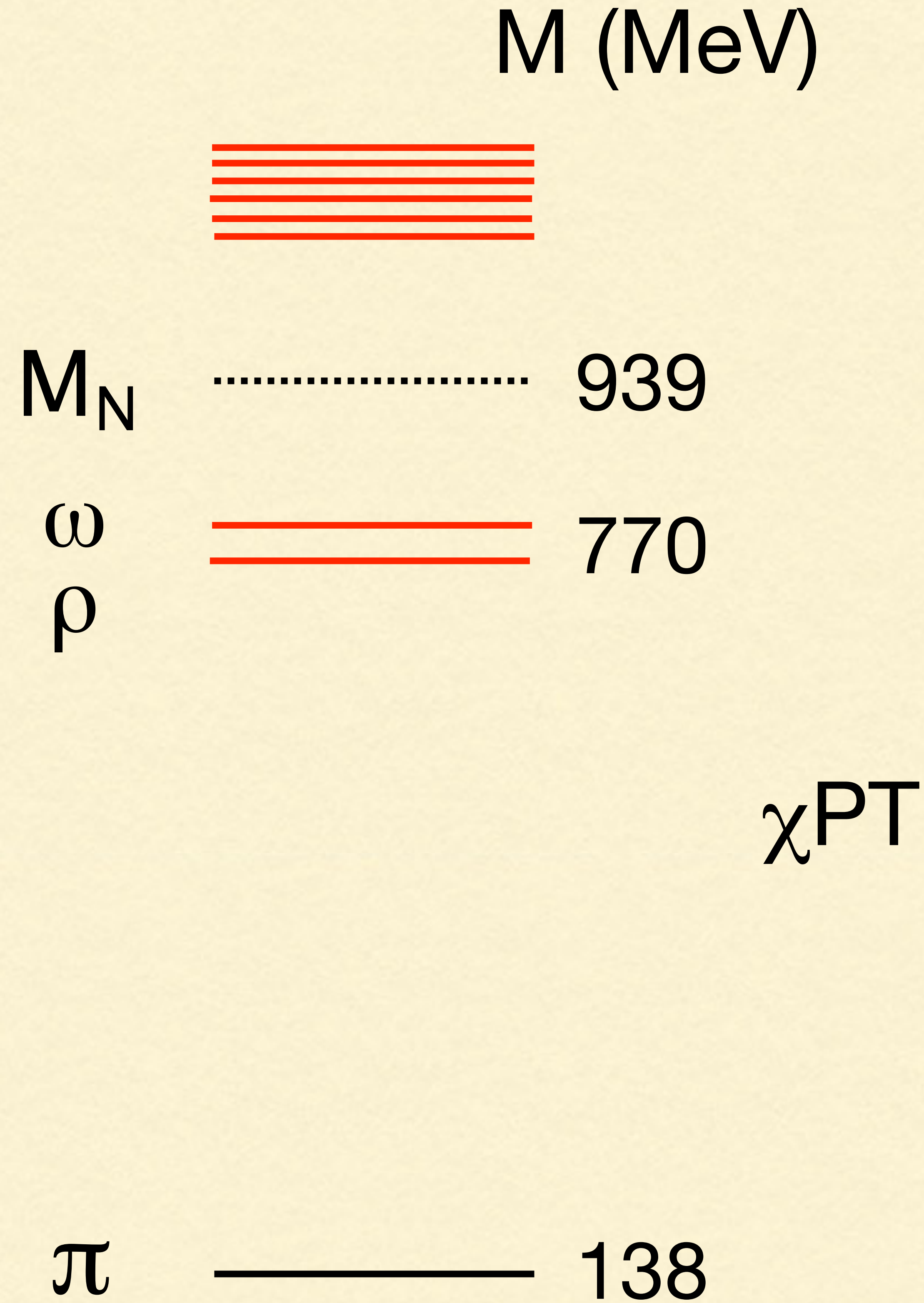
EXPRESSIONS OF CHIRAL DYNAMICS IN HADRONS AND NUCLEI

Daniel Phillips
Ohio University

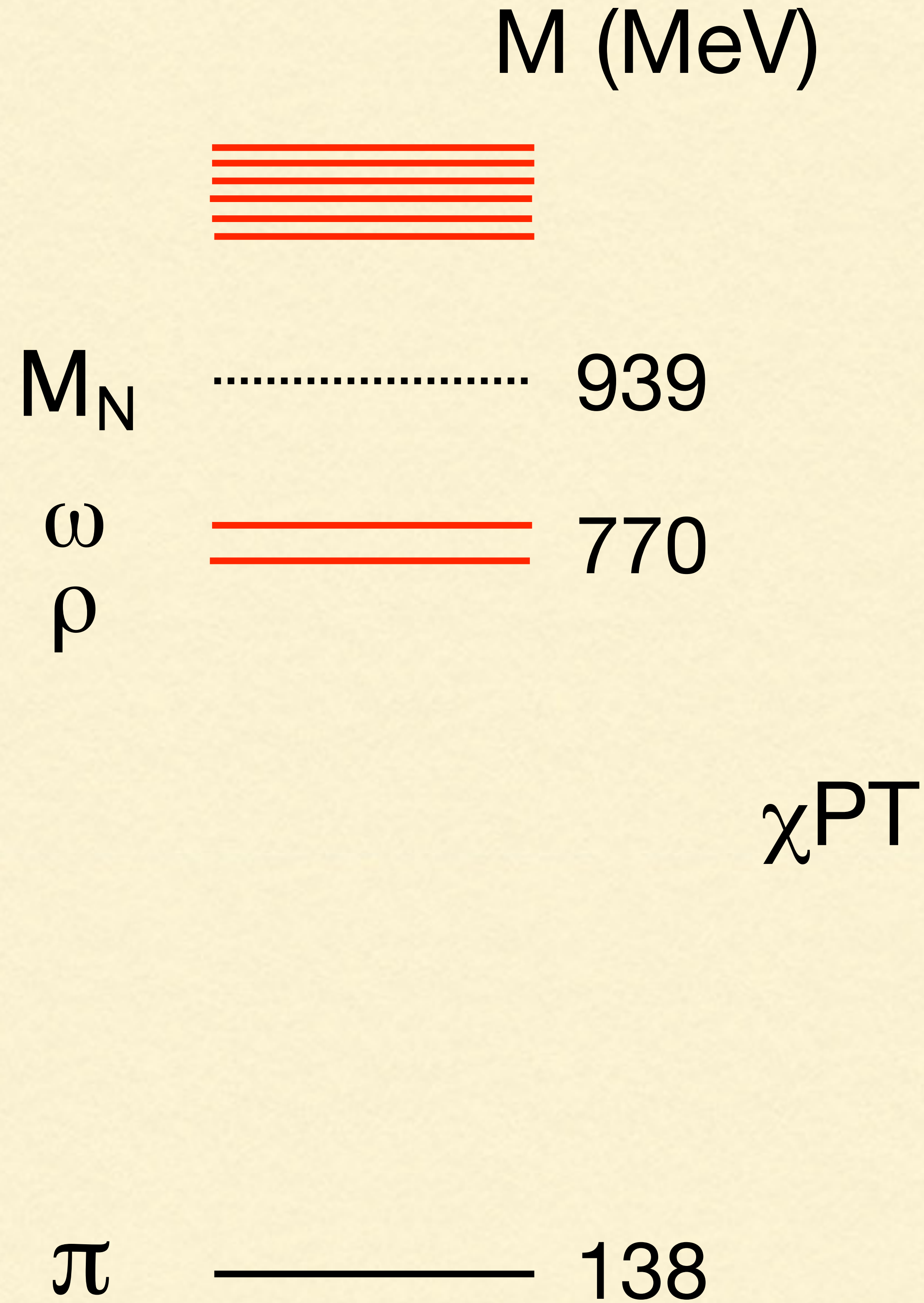
Research supported by the US Department of Energy

CHIRAL DYNAMICS



CHIRAL DYNAMICS

- For probe energies~a few hundred MeV, simplifications of the rich QCD dynamics emerge: processes dominated by πs and Δs
- BUT, interplay with other QCD states crucial in detailed comparisons with data
- EFTs provide a way to organize the theory: expansion in M_{lo}/M_{hi}→theory uncertainties
- Delineate this interplay precisely
- Possible to obtain high-accuracy hadronic numbers. Key to Intensity Frontier searches for BSM physics and determination of SM parameters.
- Here emphasis on EM probes



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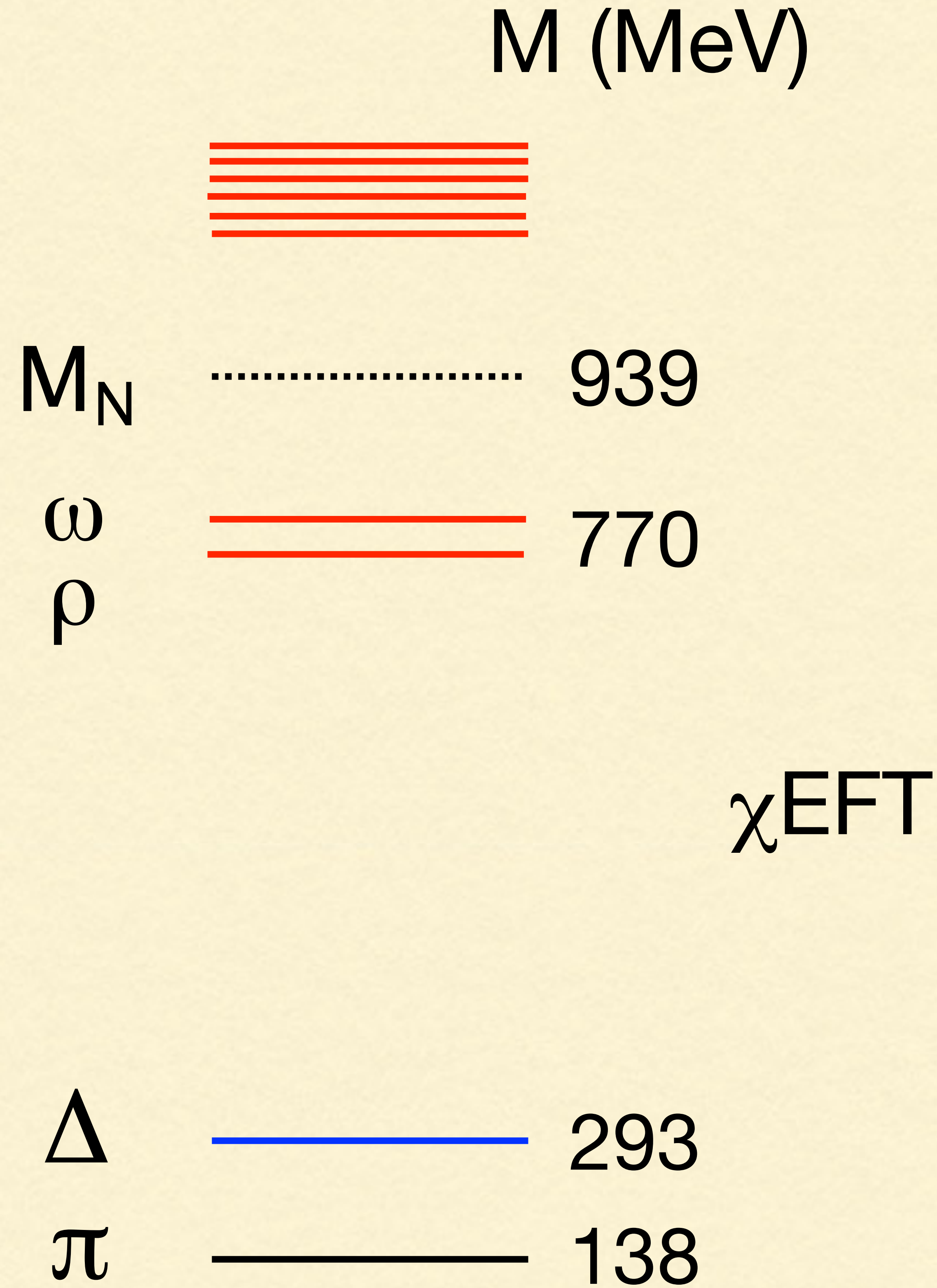

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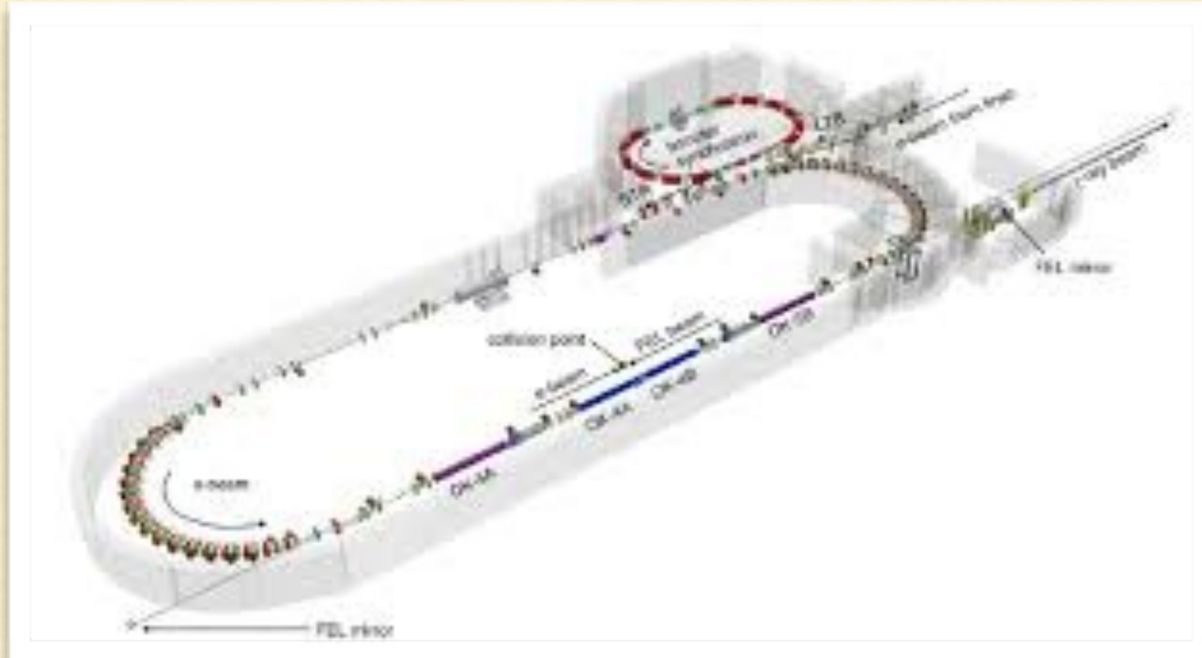
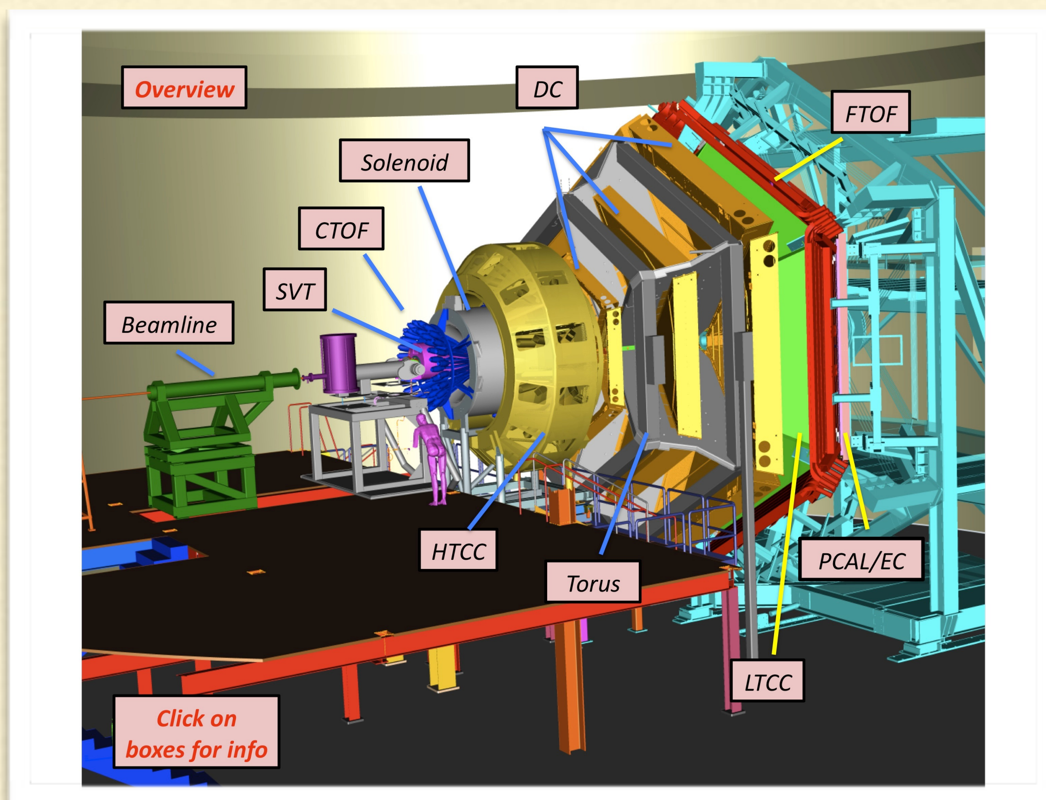
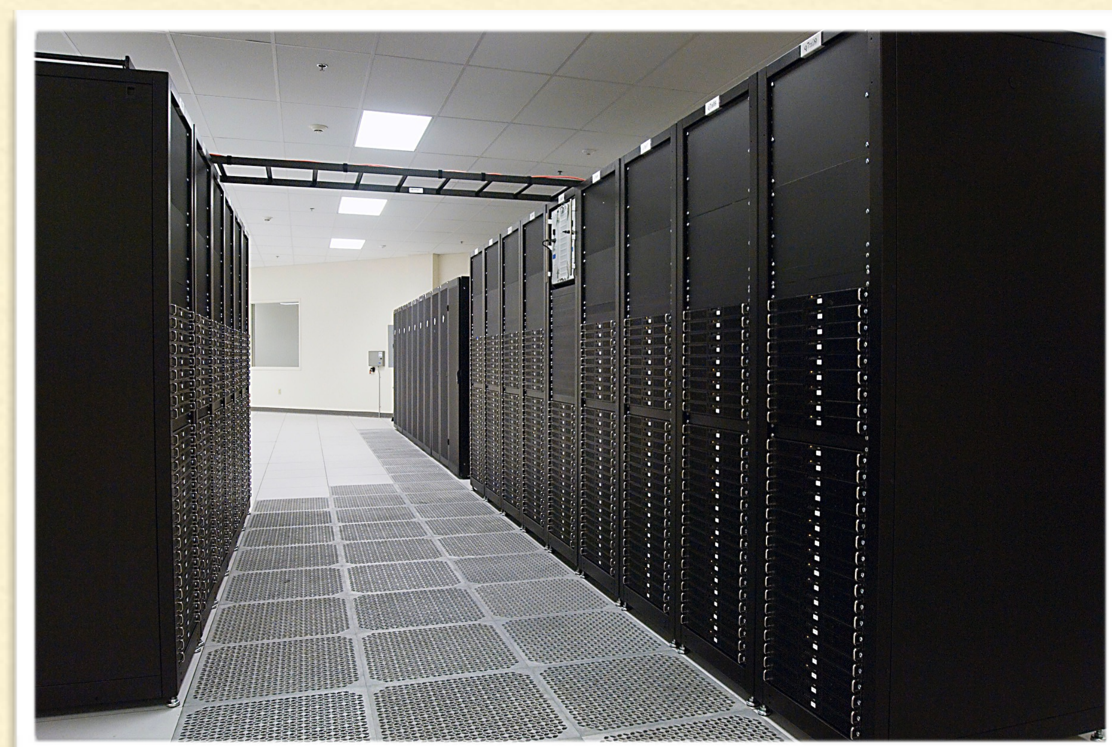
Picture credits: TUNL, JLab, ORNL







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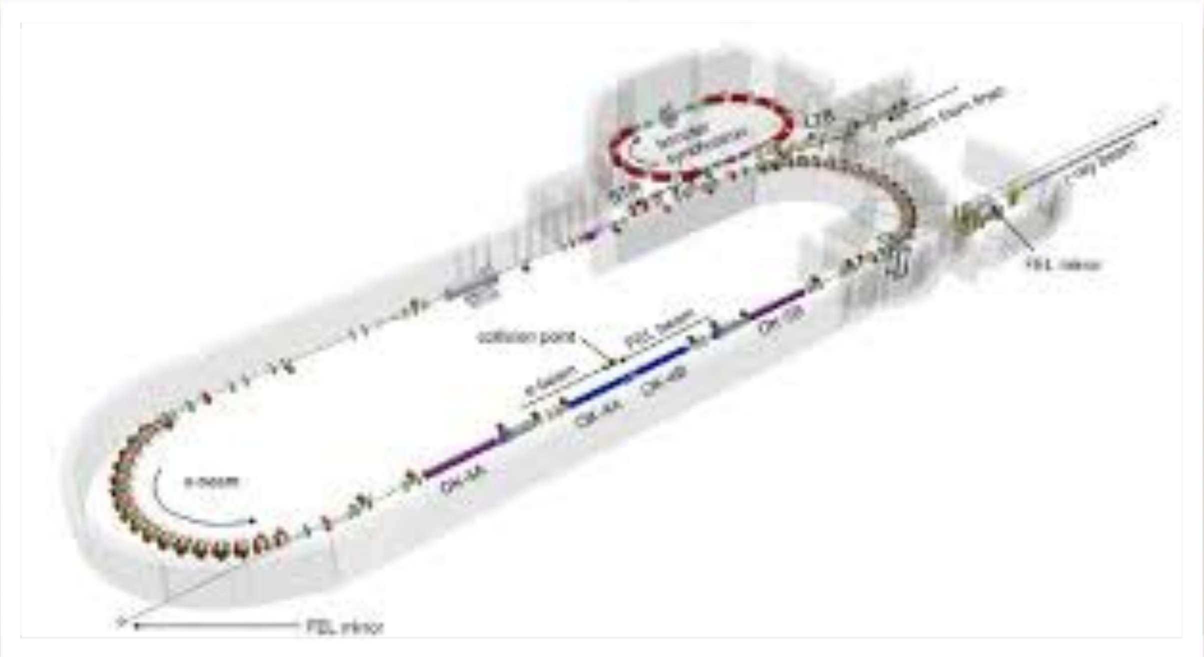
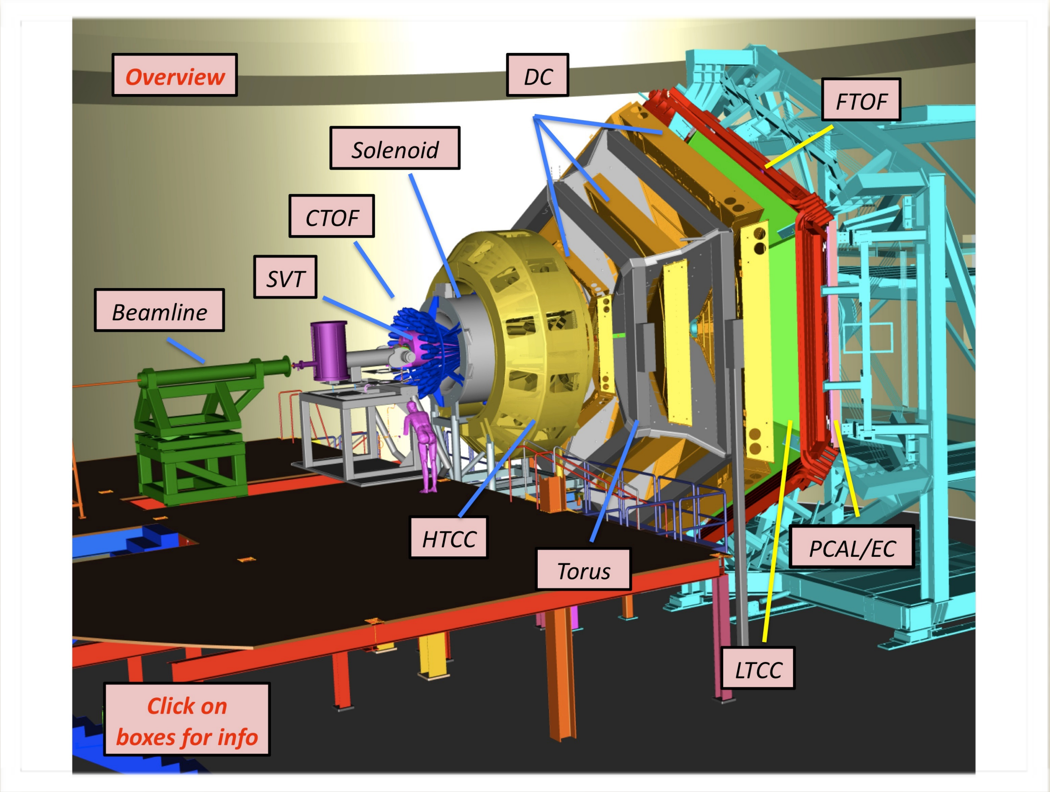
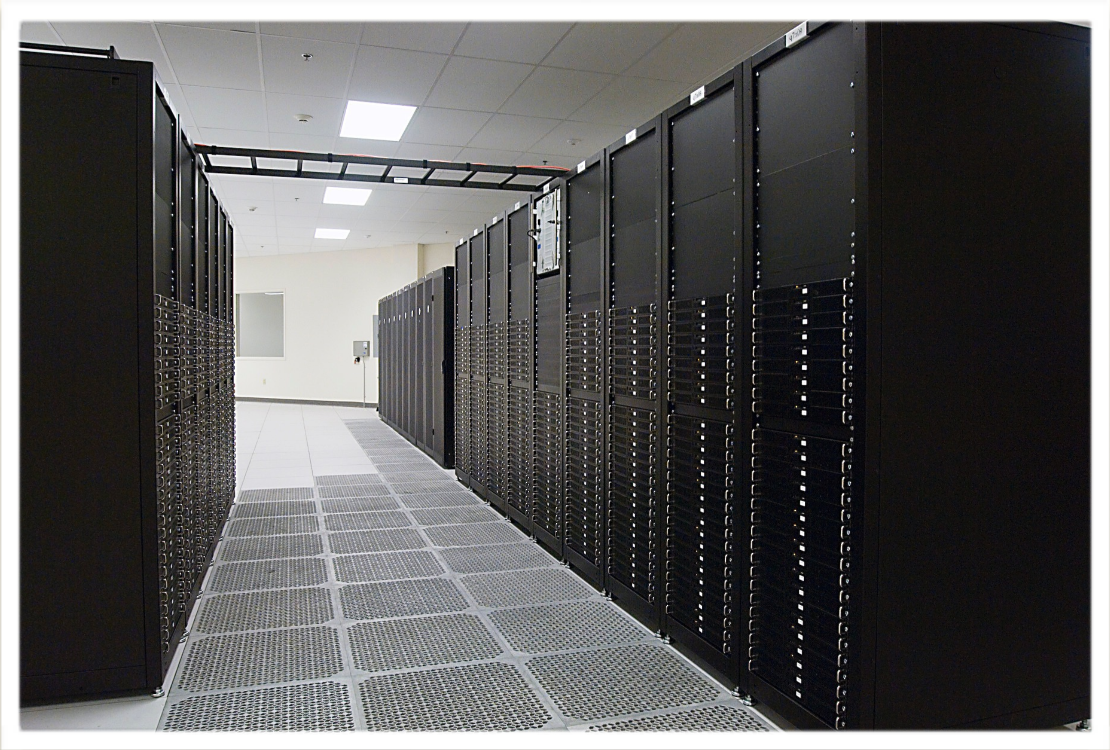
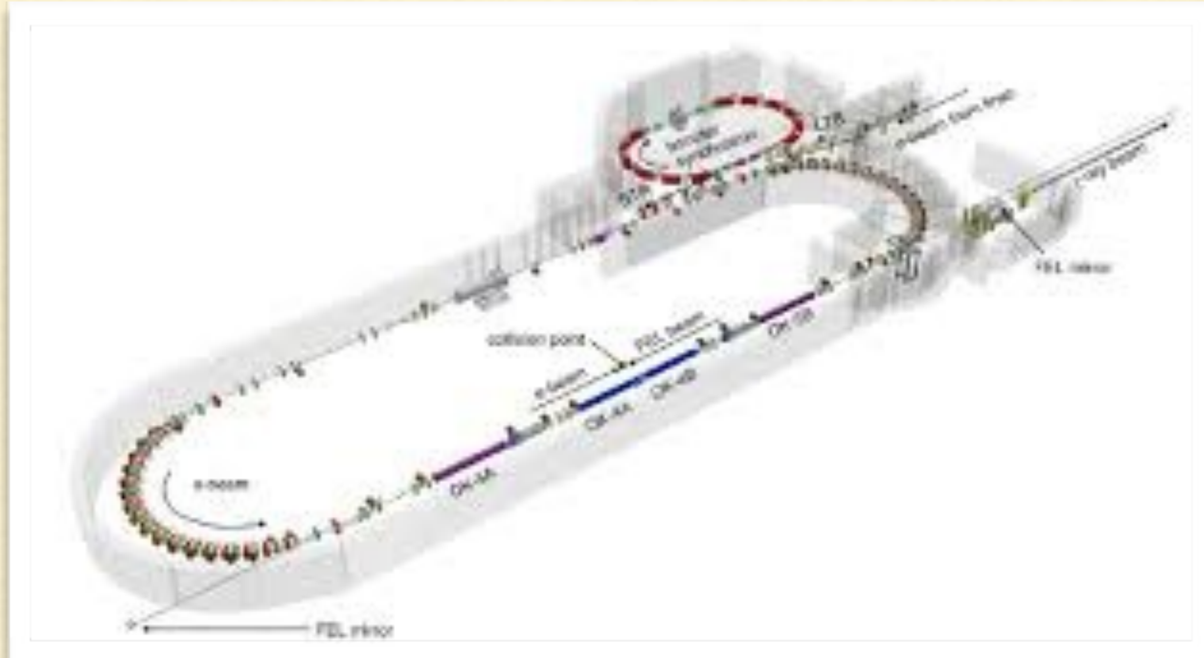


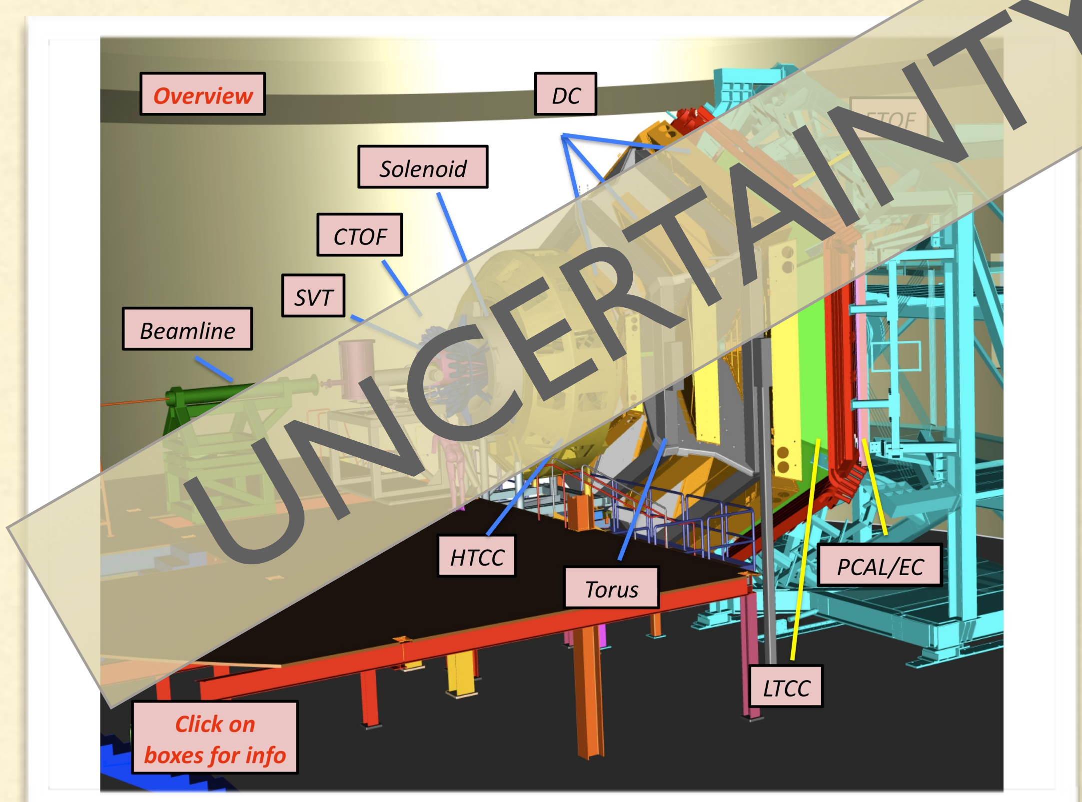
EFT

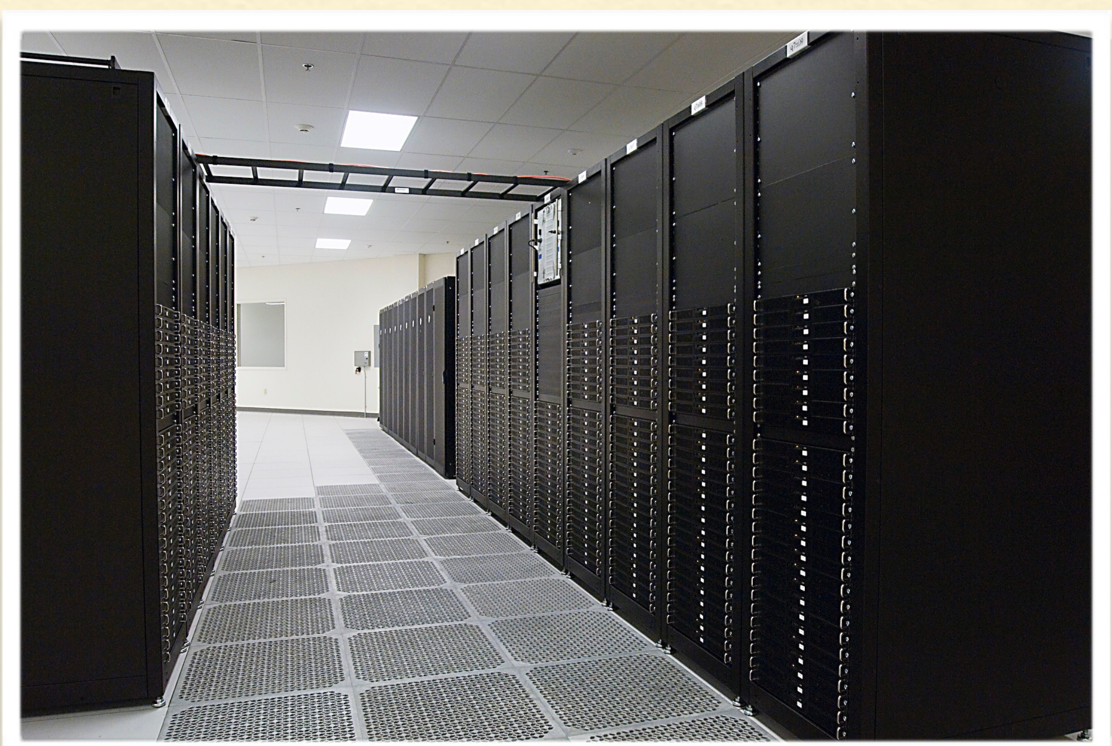






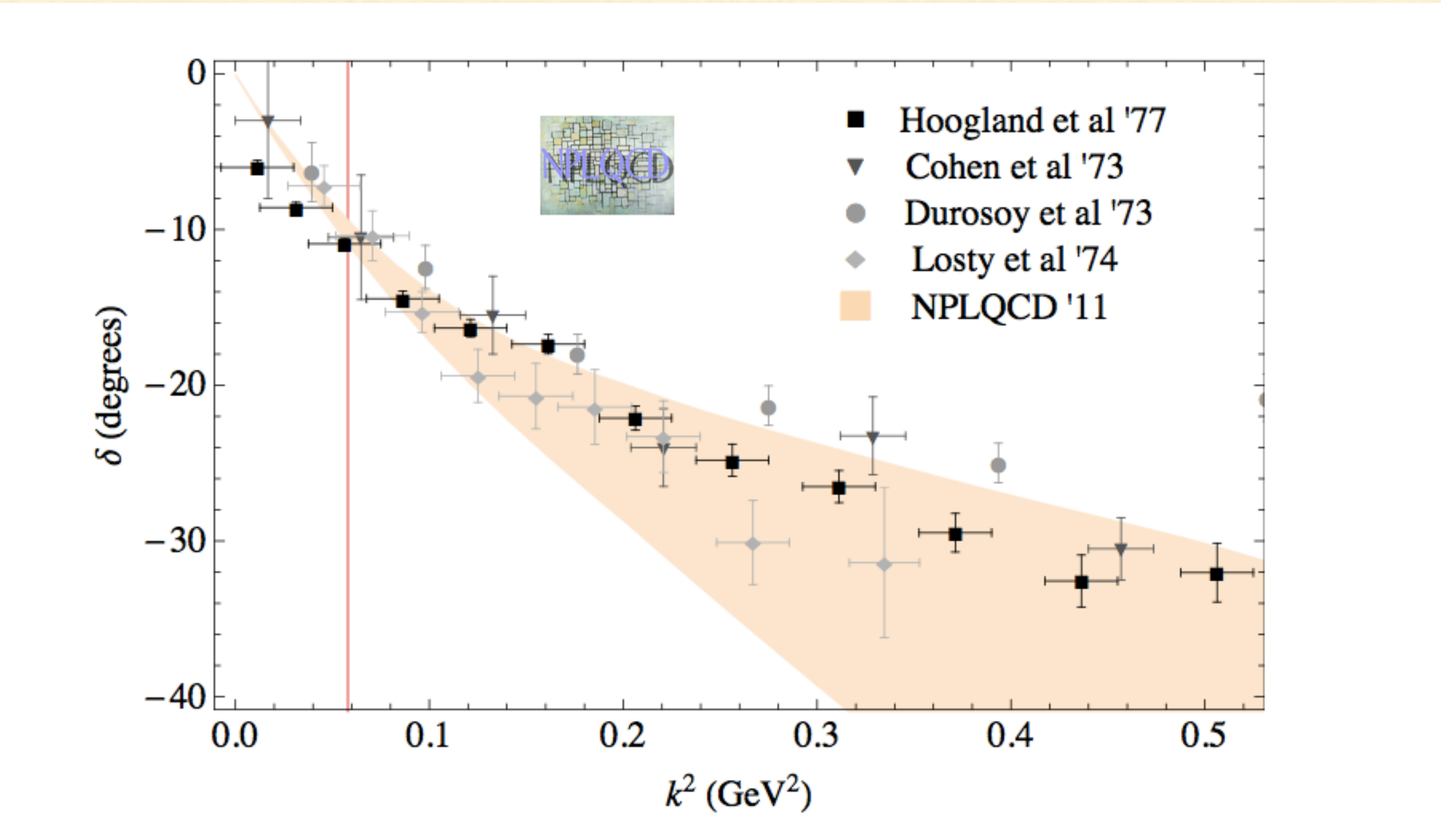
UNCERTAINTY QUANTIFICATION





A=0: $\pi\pi$ SCATTERING (I=2)

HSC, NPLQCD (2011)



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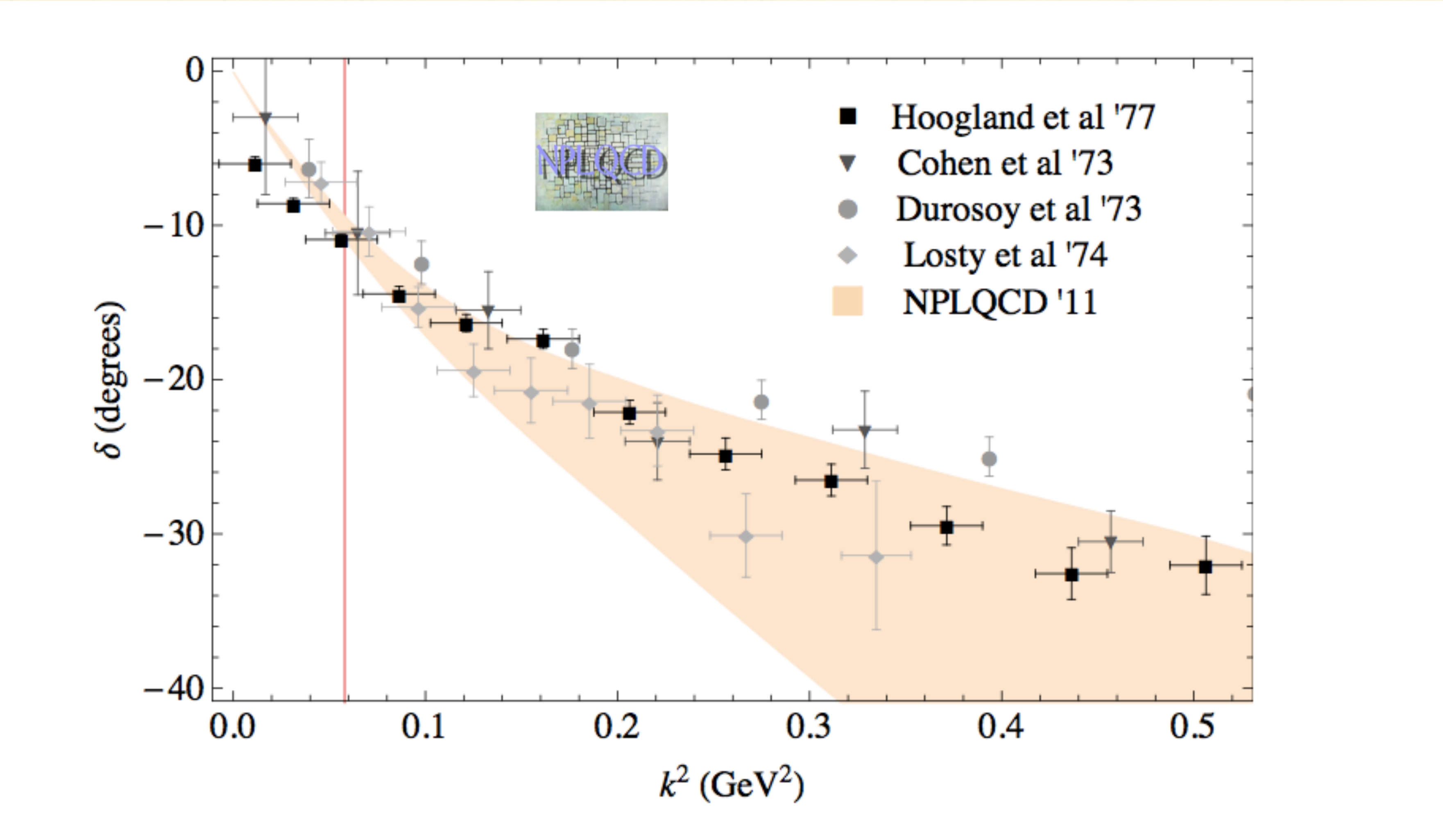

- Anisotropic n_f=2+1 clover. $m_\pi \simeq$390 MeV
- Several energy levels in the box measured, at different L. Lüscher for δ

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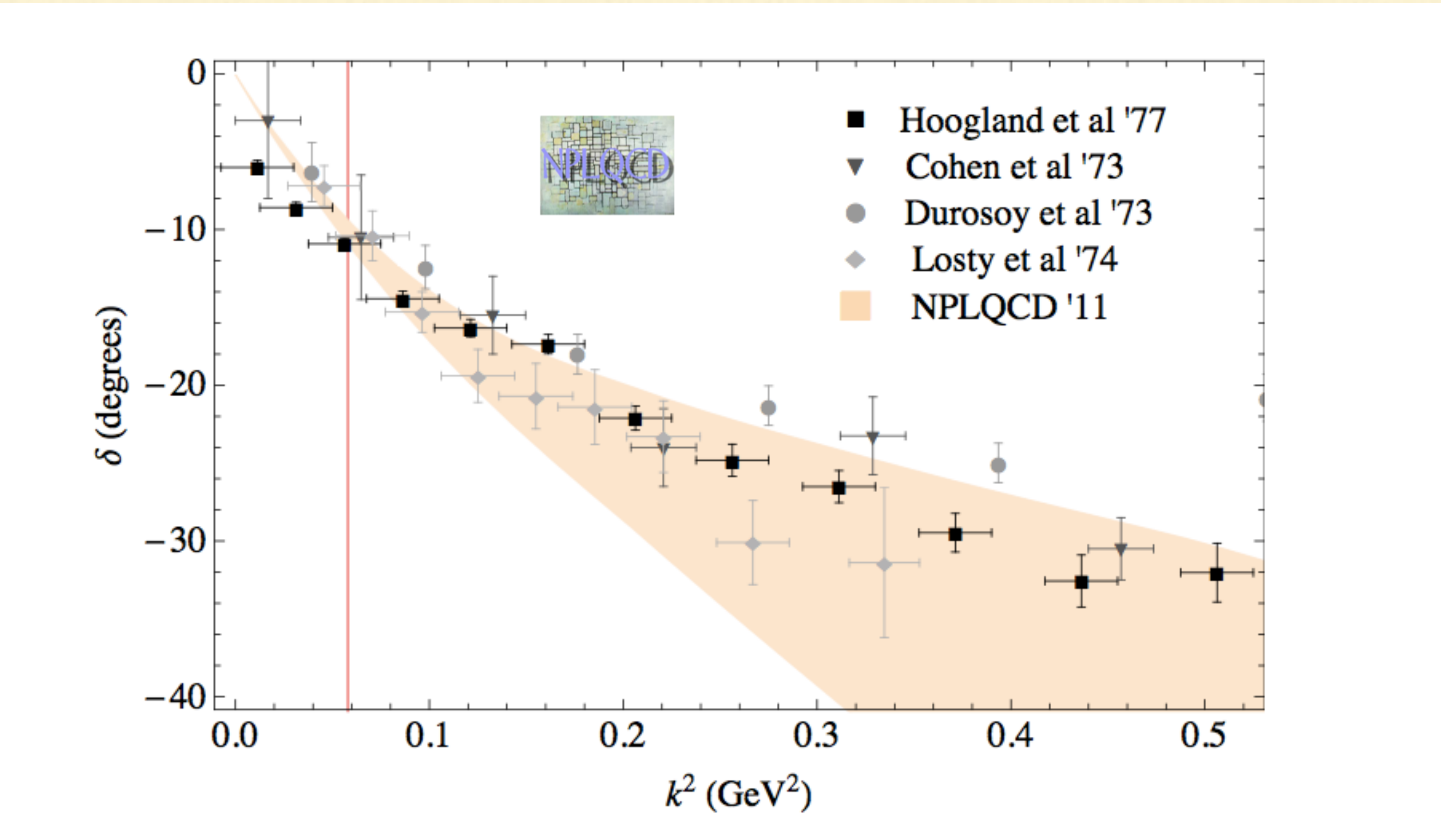

$m_\pi a$=0.0417(07)(02)(16)

NA48:
$m_\pi a$=0.0429(44)(28)

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- EFT is key to understanding both L- and m_π-dependence of LQCD data, and to extraction of scattering length from NA48 data

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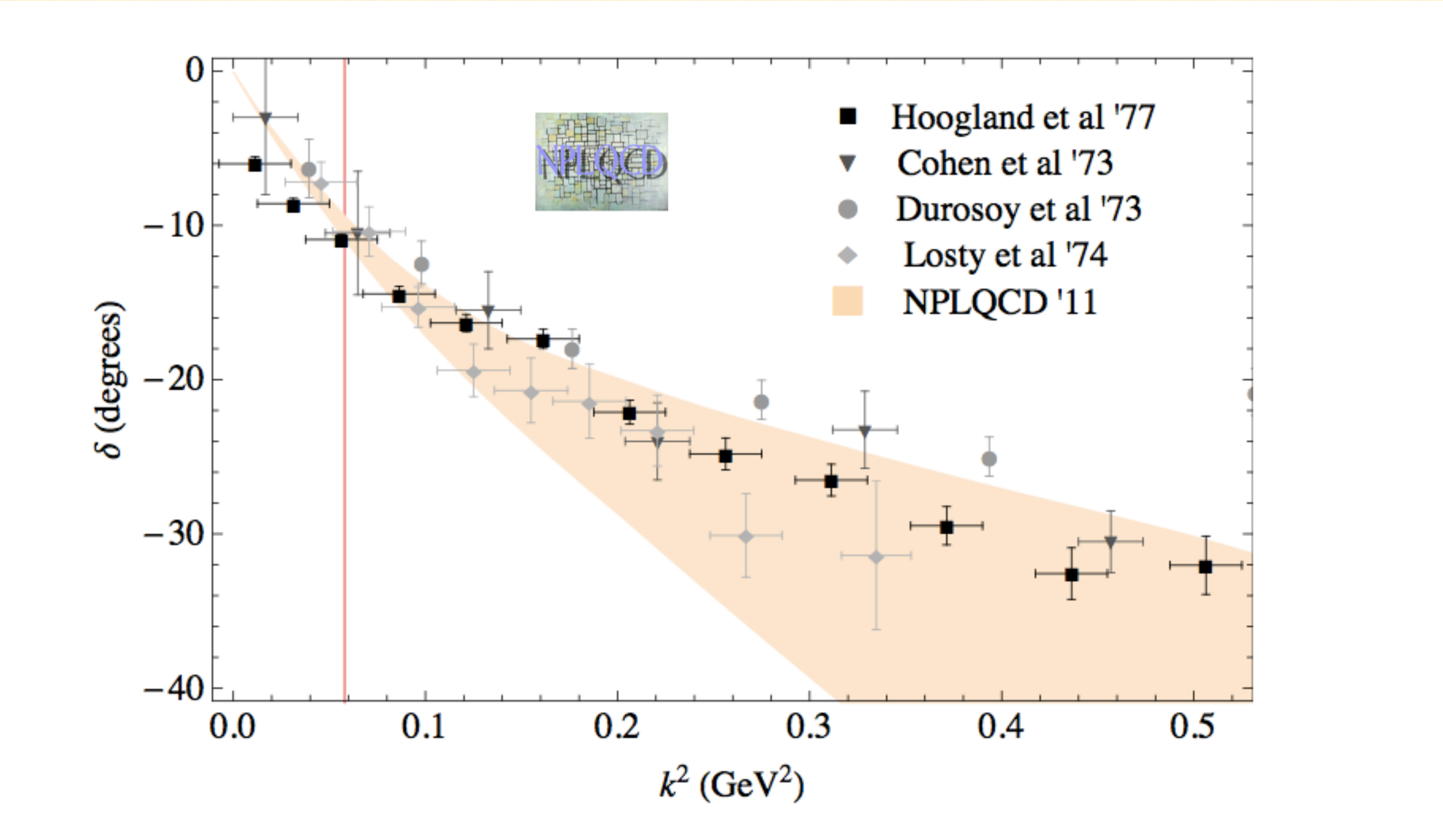

$m_\pi a$=0.0417(07)(02)(16)

NA48:
$m_\pi a$=0.0429(44)(28)

Roy equations:
$m_\pi a$=0.0444(1)

Colangelo, Gasser, Leutwyler (2001)

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$\gamma\gamma \rightarrow \pi\pi$ AND π POLARIZABILITIES

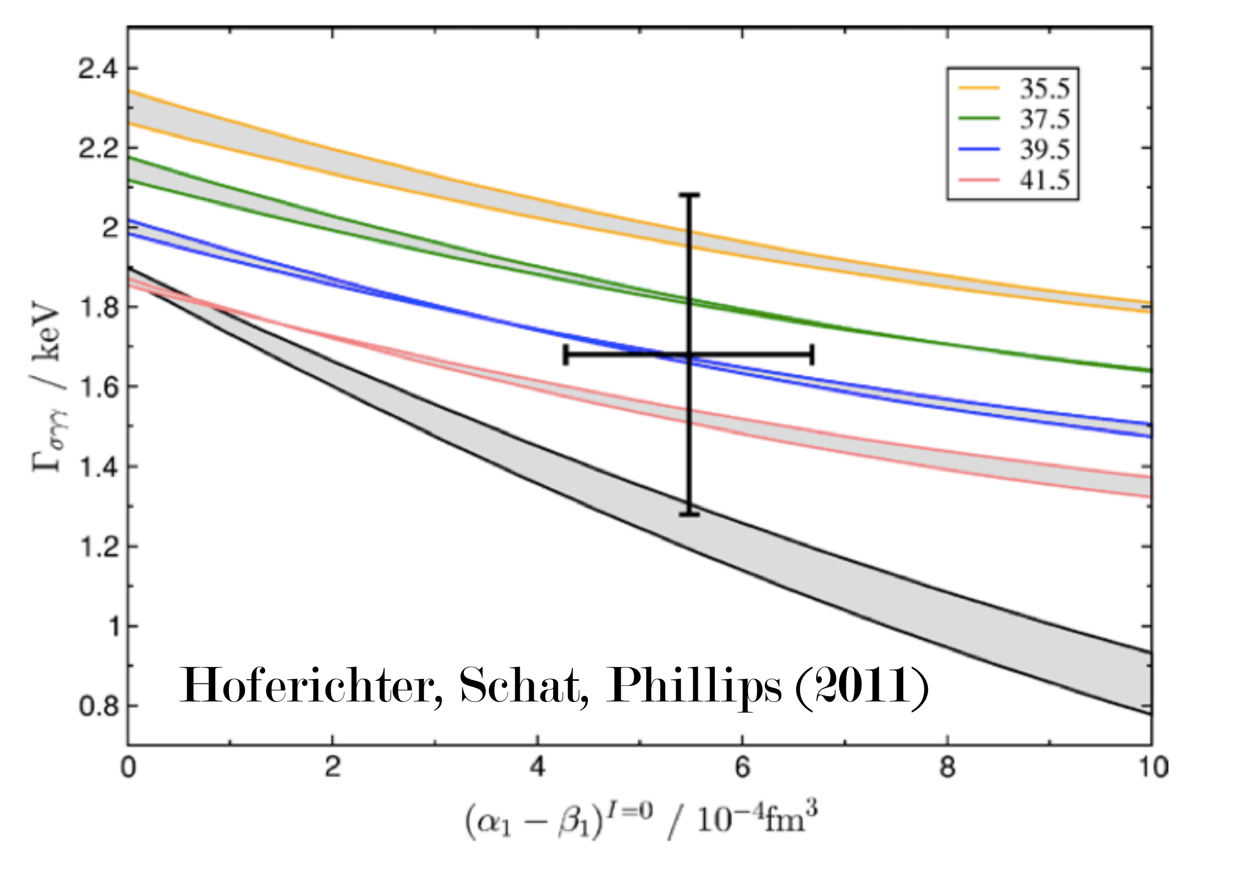
- Roy equations=dispersion relations + partial-wave expansion + crossing symmetry + unitarity⇒Coupled set of equations for partial-wave amplitudes

- Ensuring low-energy amplitude matches to χPT and using data at energies > 1 GeV as input gives accurate ππ phase shifts over a wide energy range

- Sigma resonance pole position: $M_\sigma = 441^{+16}_{-8}\text{MeV}; \quad \Gamma_\sigma = 554^{+18}_{-25}\text{MeV}$

Caprini, Colangelo, Leutwyler (2006)

- Roy-Steiner equations for γγ→ππ. Subtractions suppress left-hand cut



Hoferichter, Schat, Phillips (2011)

χPT input for π polarizabilities⇒

$$\Gamma_{\sigma\gamma\gamma} = (1.7 \pm 0.4)\ \text{keV}$$

COMPASS:

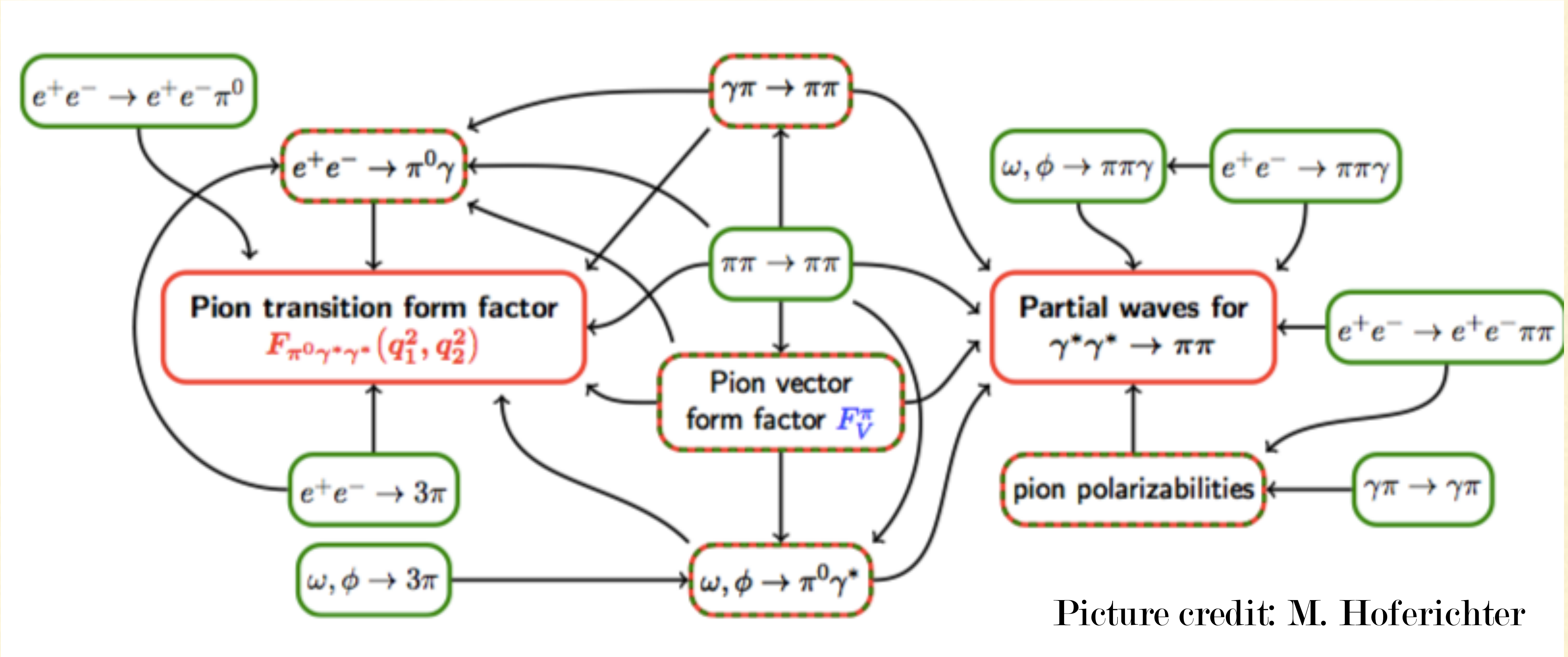
$$\alpha_\pi = (1.9 \pm 0.7_{\text{stat.}} \pm 0.8_{\text{sys.}}) \times 10^{-4}\ \text{fm}^3$$

JLab Hall D: PR-13-008, A- rating

Spokesperson: R. Miskimen (U. Mass.)

DOING BETTER ON HADRONIC LBL

Data + dispersion relations with chiral constraints

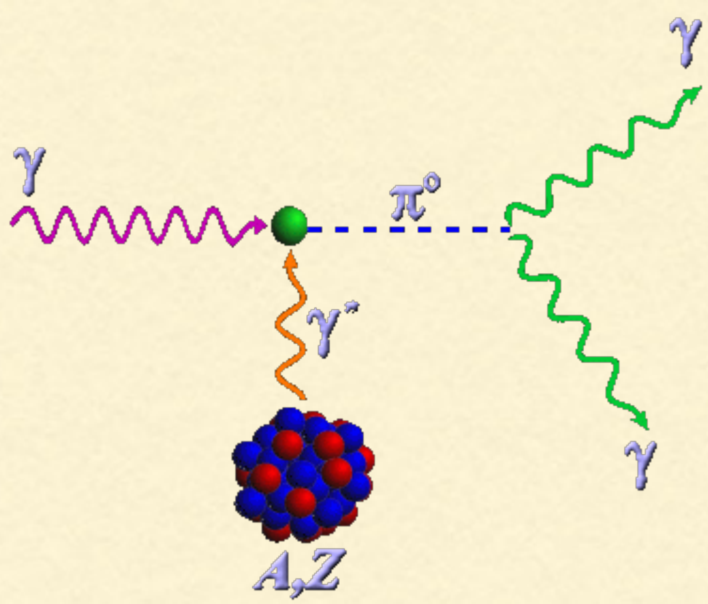


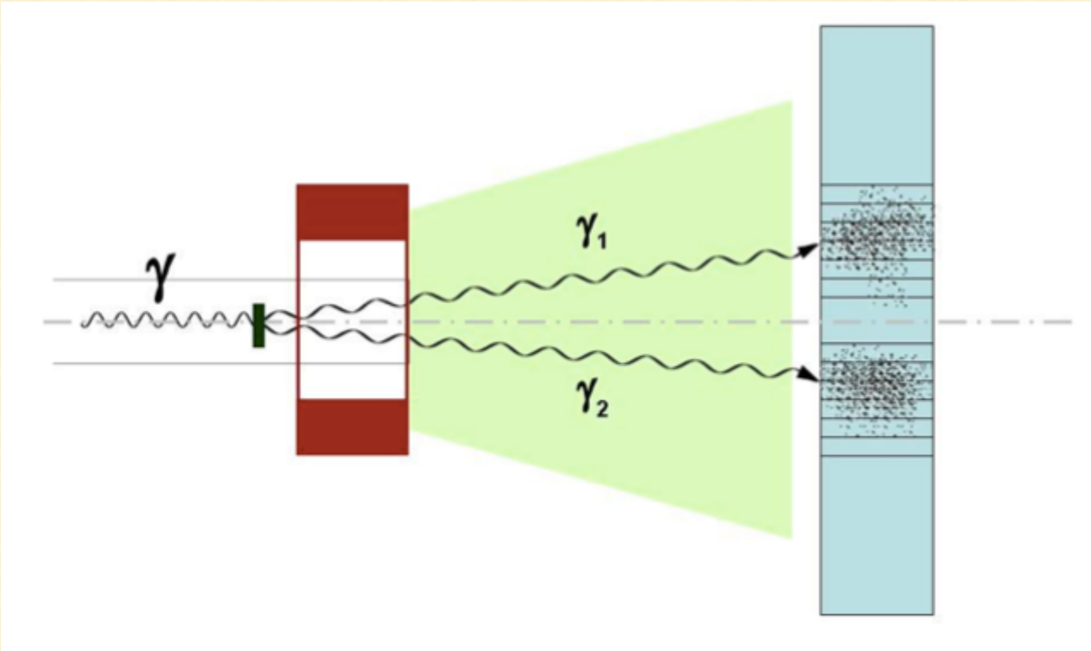
UNCERTAINTY QUANTIFICATION

- Reconstruction of $\gamma^* \gamma^* \to \pi\pi, \pi^0$: combine experiment and theory constraints
- Next step: η, η', KKbar, multi-pion channels, pQCD constraints for high energy
- Measured resonance parameters play a key role in constraining this analysis

PRIMEX AND PRIMEX-II

Picture credit: PRIMEX

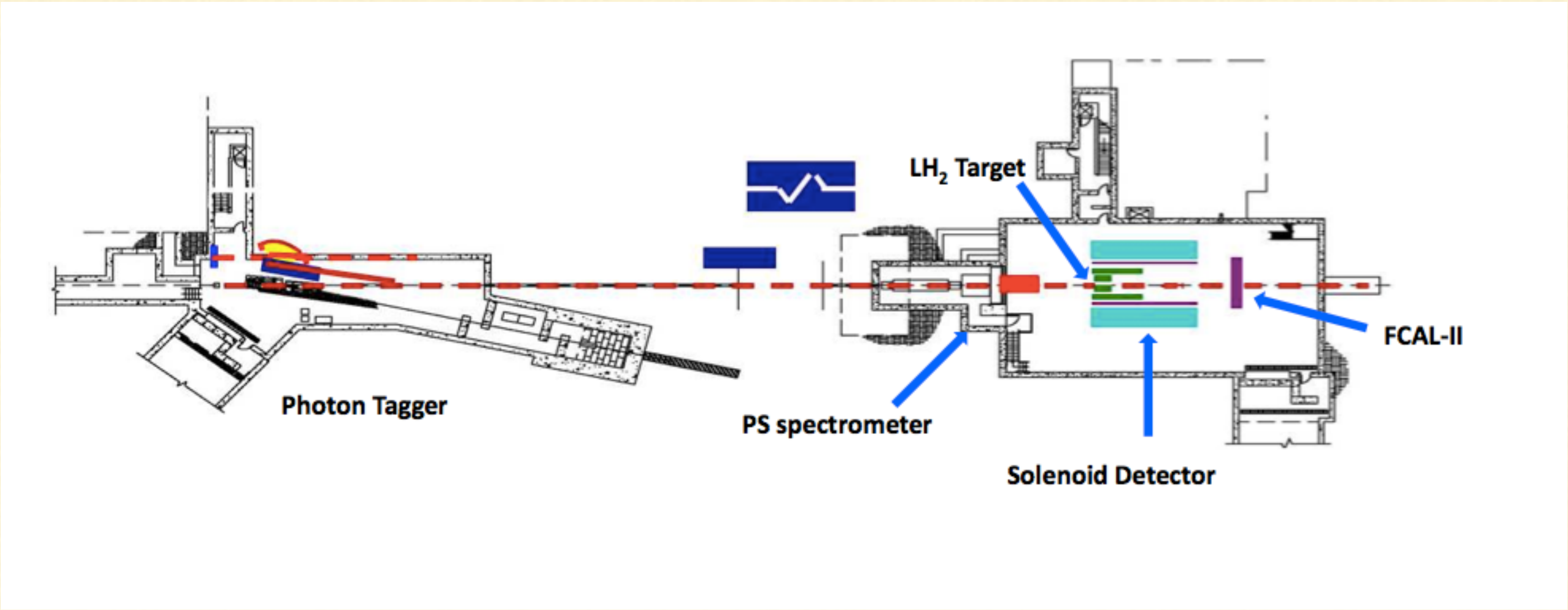




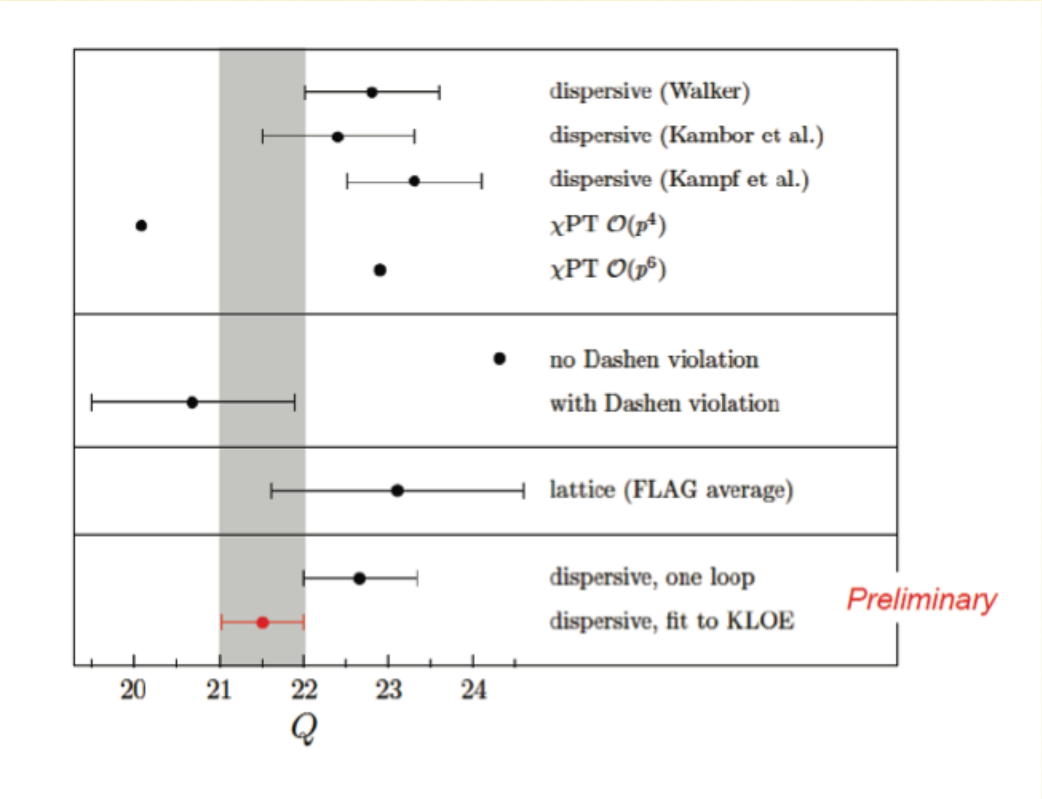
- Fixes normalization of pion transition form-factor: input for hadronic LbL
- χPT at O(p⁴): $\Gamma(\pi^0 \to \gamma\gamma) = \dfrac{\alpha_{\rm em}^2 N_c^2 m_\pi^3}{576\pi^3 f_\pi^2} = 7.725\ \text{eV}$
- O(p⁶) χPT: $\Gamma(\pi^0 \to \gamma\gamma) = (8.10 \pm 0.08)\ \text{eV}$
- PRIMEX: $\Gamma(\pi^0 \to \gamma\gamma) = (7.82 \pm 0.17_{\rm stat.} \pm 0.16_{\rm syst.})\ \text{eV}$
- PRIMEX-II to shrink error bar by factor of 2

THE JLAB ETA FACTORY

Picture credits: JEF proposal



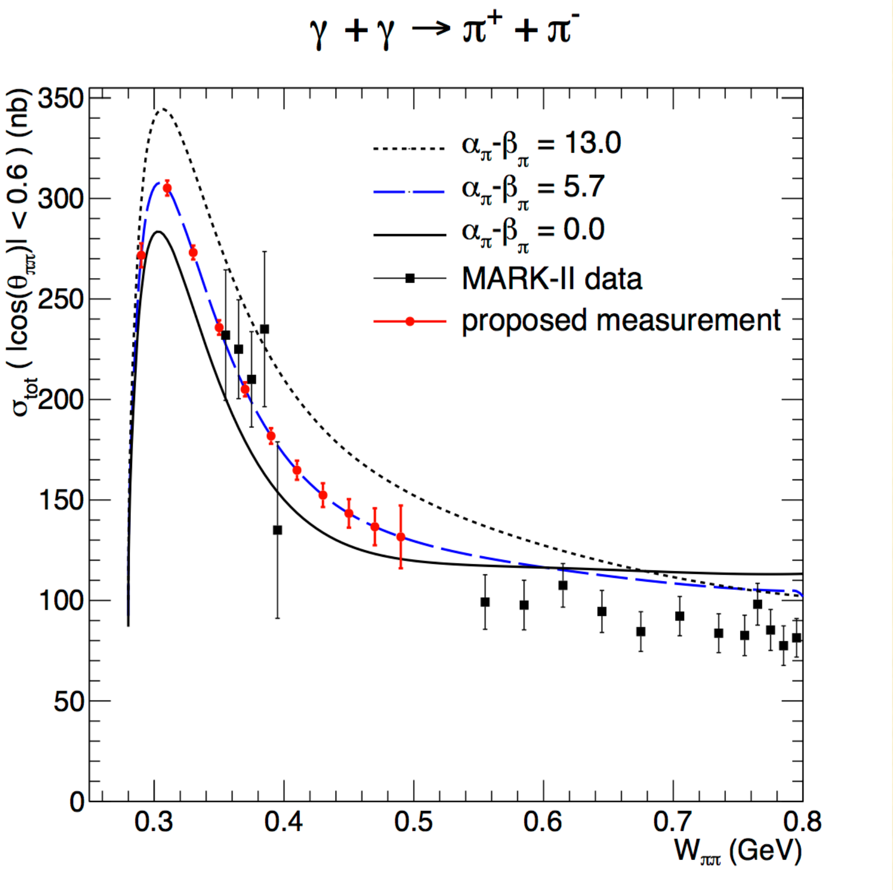
- JEF will improve limits on rare C-violating η decays
- Improved $(m_d-m_u)/m_s$ from $\eta\to 3\pi$: precise determination of SM parameter
- Go beyond naive χPT expansion: unitarization.

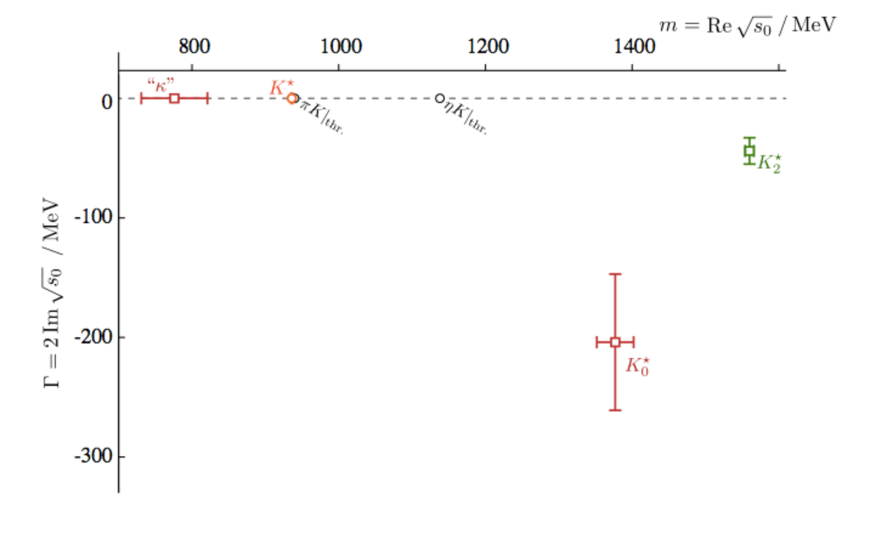


FUTURE OPPORTUNITIES: A=0

Picture credits: R. Miskimen, J. Dudek et al.

- Two-loop [$O(p^6)$] χPT for π properties now standard; high-accuracy calculations routine.
- Convergence in SU(3) not as good. Uncertainty quantification a challenge for initial states with M~1 GeV.
- Increasingly precise LQCD numbers for pion dynamics, at lower pion masses
- A=0 resonances from LQCD: ρ, strange states, ….
- Dispersion relations/unitarized ChiPT/models will connect both experiment and lattice to resonance properties.
- Dispersion relations for HLbL: follow the roadmap
- 12 GeV JLab: PRIMEX-II, π polarizability, η factory



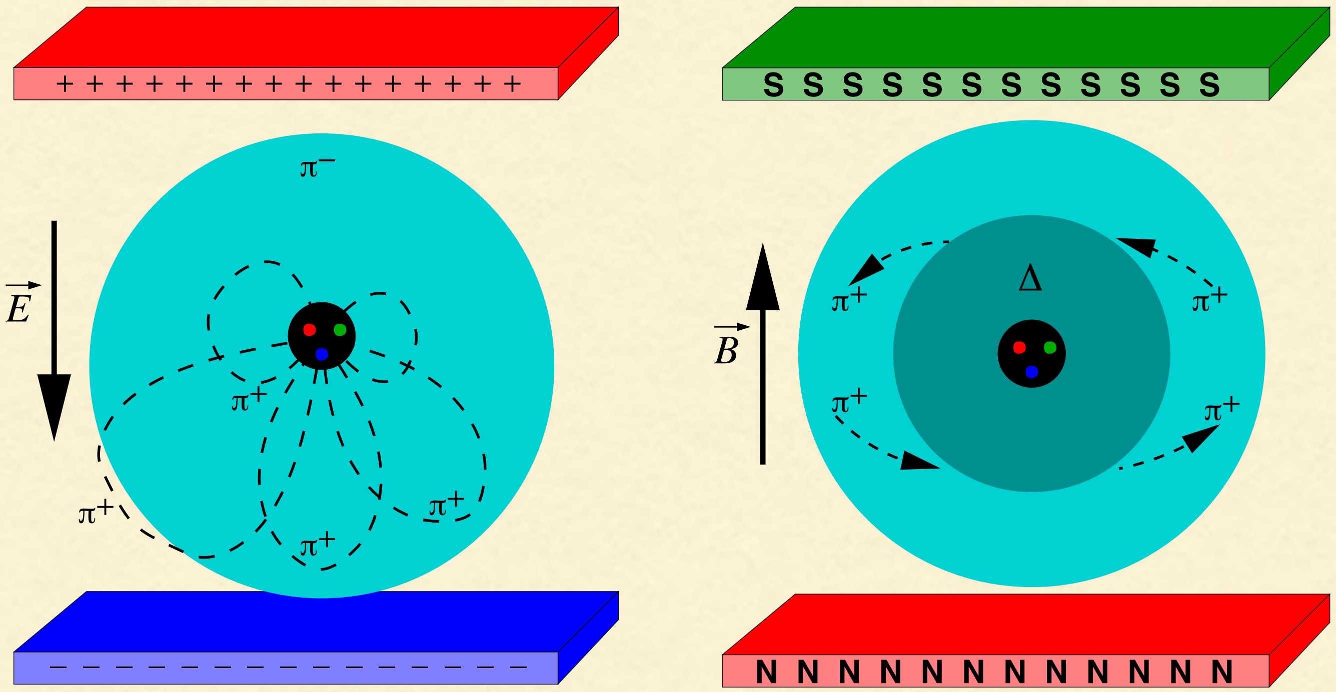


A=1: MOSTLY COMPTON

- Traditionally: "tests of chiral symmetry" in near-threshold pion photoproduction
- Emergent dynamics of strong QCD, but why these matrix elements?
- Here emphasis is on Compton scattering, especially the quest to measure electromagnetic polarizabilities of the proton (neutron in A=2 section)
    - Probe chiral dynamics *below pion threshold*
    - LQCD error bars commensurate with experiment→TIBURZI
    - Key inputs in forefront SM parameter extractions and tests: M_n-M_p, μH, …
- Ability to quantify theory uncertainty is key to reliable extraction of hadronic matrix elements

STATIC AND DYNAMIC POLARIZABILITIES

Picture credit: H. Grießhammer



$$H = -2\pi[\alpha_{E1}\mathbf{E}^2 + \beta_{M1}\mathbf{B}^2 + \ldots]$$

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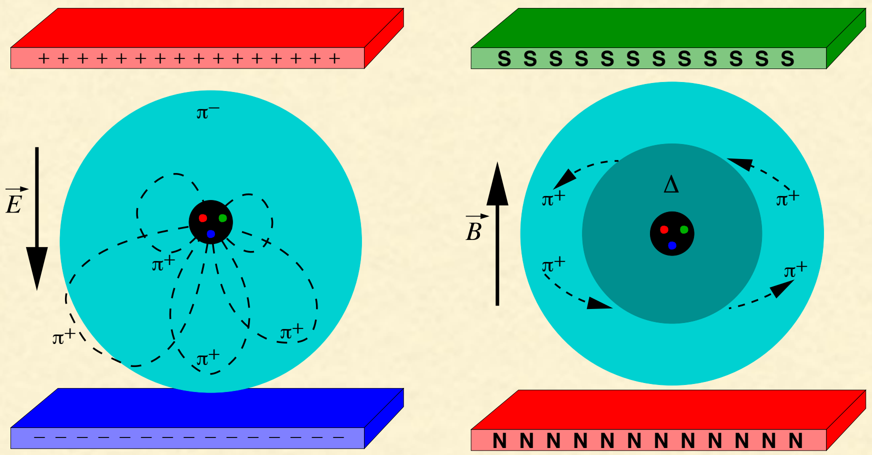

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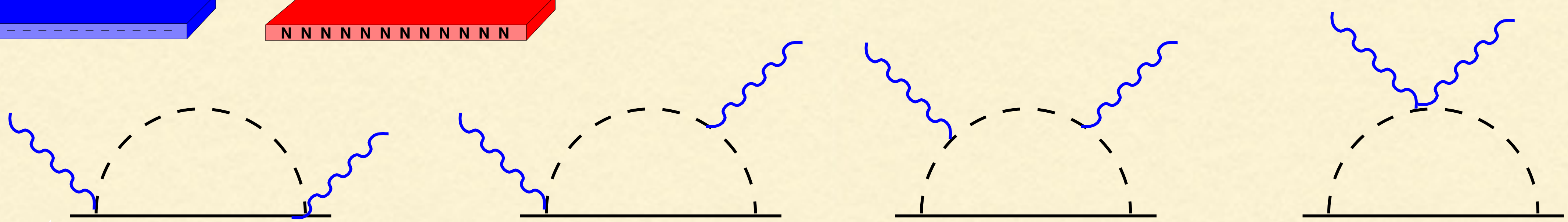


- Δ-less χPT at O(P³): $\alpha_{E1}^{(p)} = 10\beta_{M1}^{(p)} = \dfrac{5e^2 g_A^2}{384 f_\pi^2 m_\pi} = 12.5 \times 10^{-4}\ \mathrm{fm}^3$
- But χPT predicts entire energy dependence of amplitudes, so define:

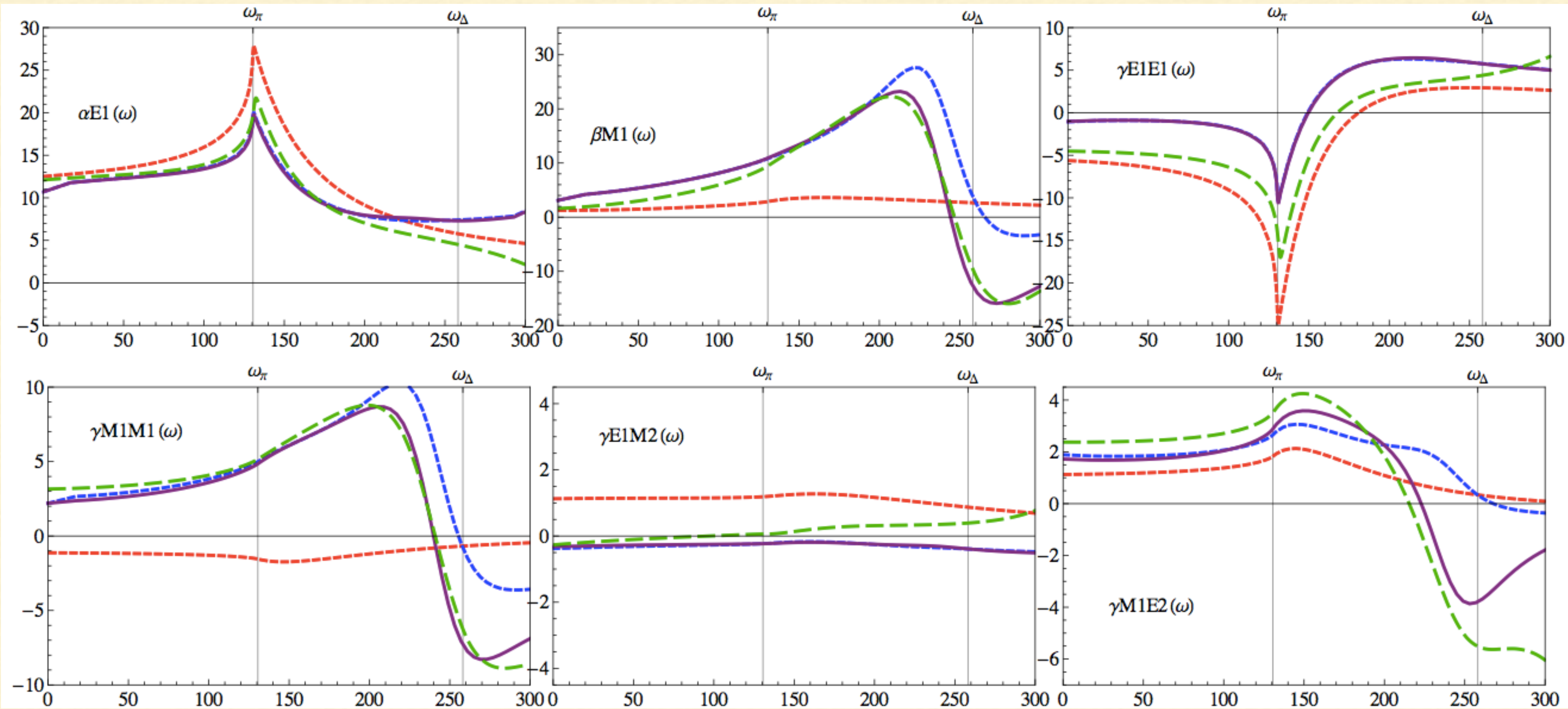
$$H = -2\pi[\alpha_{E1}(\omega)\mathbf{E}^2 + \beta_{M1}(\omega)\mathbf{B}^2 + \gamma_{E1E1}(\omega)\sigma\cdot(\mathbf{E}\times\dot{\mathbf{E}})$$
$$+\gamma_{M1M1}(\omega)\sigma\cdot(\mathbf{B}\times\dot{\mathbf{B}}) - 2\gamma_{M1E2}(\omega)\sigma_i B_j E_{ij} + 2\gamma_{E1M2}(\omega)\sigma_i E_j B_{ij} + \ldots]$$

- Numerically: six dynamical polarizabilities reproduce Compton observables up to 300 MeV to a few per cent: partial-wave analysis of γp

(Was made rigorous via multipole expansion of different invariant amplitudes.)

DYNAMICAL POLARIZABILITIES

Grießhammer, McGovern, Phillips, Feldman



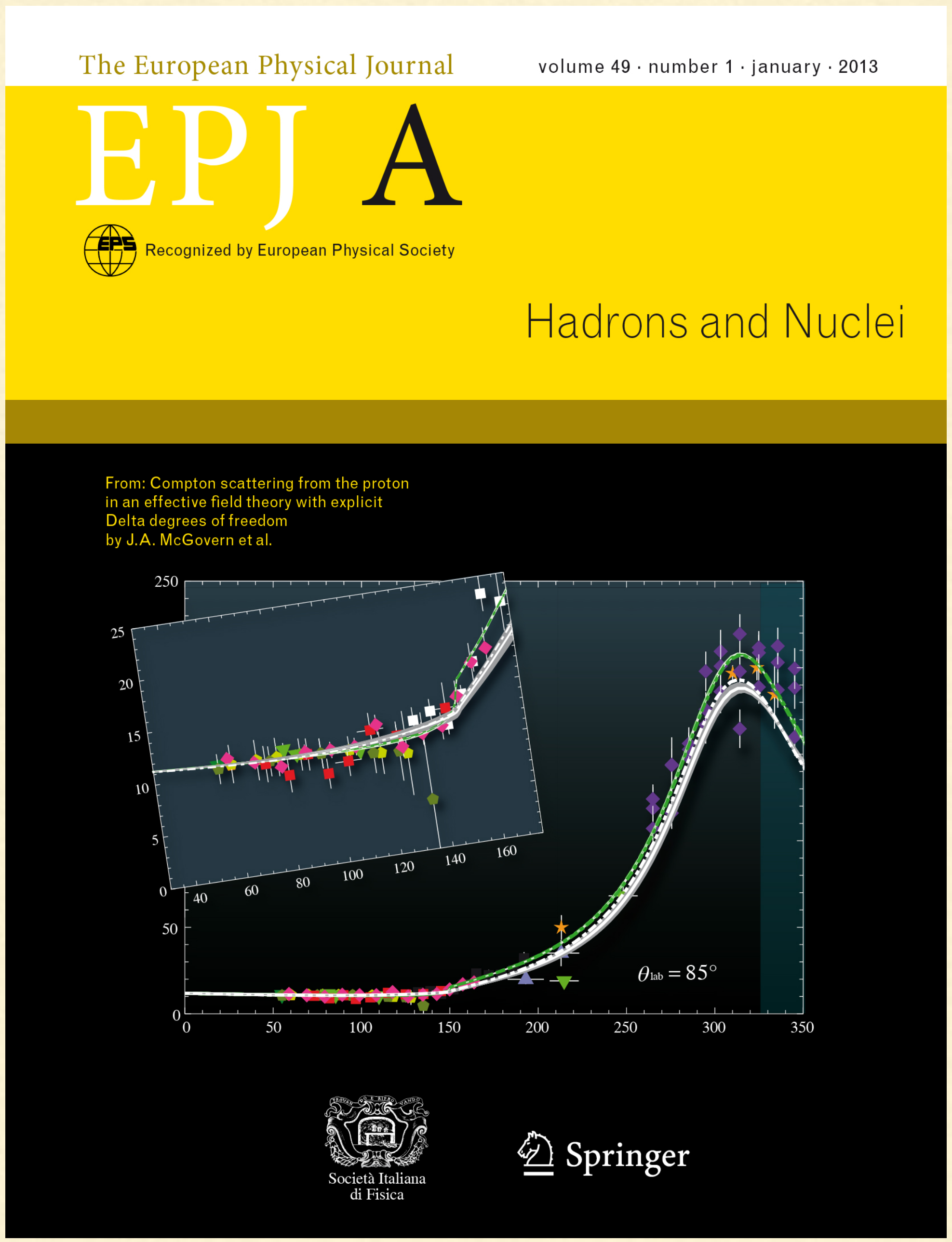
- Remarkable concordance of various theories on energy dependence of dynamical polarizabilities below 200 MeV.

Grießhammer, L'vov, McGovern, Pascalutsa, Pasquini, Phillips, arXiv:1409.1512

- Suggests: (a) experiments should be done in this regime in order to minimize theory uncertainties; (b) best to fit all six static pols to experiment.

NEW ANALYSIS OF γ-PROTON DATA

- Ingredients: χPT Nπ loops up to O(P^4) + Dynamical Δ + $\Delta\pi$ loops + Δ width and dressed $\gamma N\Delta$ vertex [up to O($e^2\ \delta^4$)]: three free parameters



- Good reproduction of data up to ≈350 MeV
- Develop world database up to 200 MeV (incl. treatment of systematic errors). Greater theory accuracy compared to Δ region (N^4LO vs NLO).
- Fit to world γp data up to 170 MeV:

χ^2/d.o.f.=110.5/134

$$\alpha_{E1}^{(p)} = 10.65 \pm 0.35(\text{stat}) \pm 0.2(\text{Baldin}) \pm 0.3(\text{theory});$$
$$\beta_{M1}^{(p)} = 3.15 \mp 0.35(\text{stat}) \pm 0.2(\text{Baldin}) \mp 0.3(\text{theory})$$

McGovern, Grießhammer, Phillips (2013)

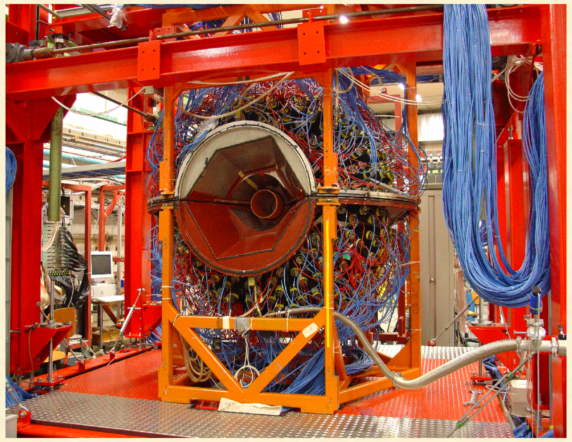
- $\beta_{M1}^{(p)}$ markedly higher than in previous (DR) fits (although marginally consistent within error bars)

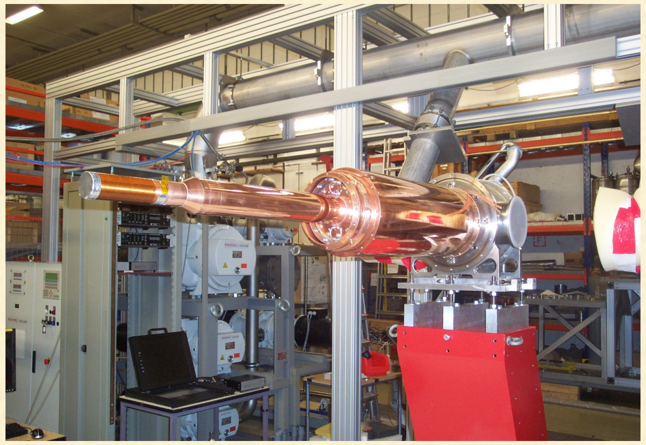
SPIN POLARIZABILITIES

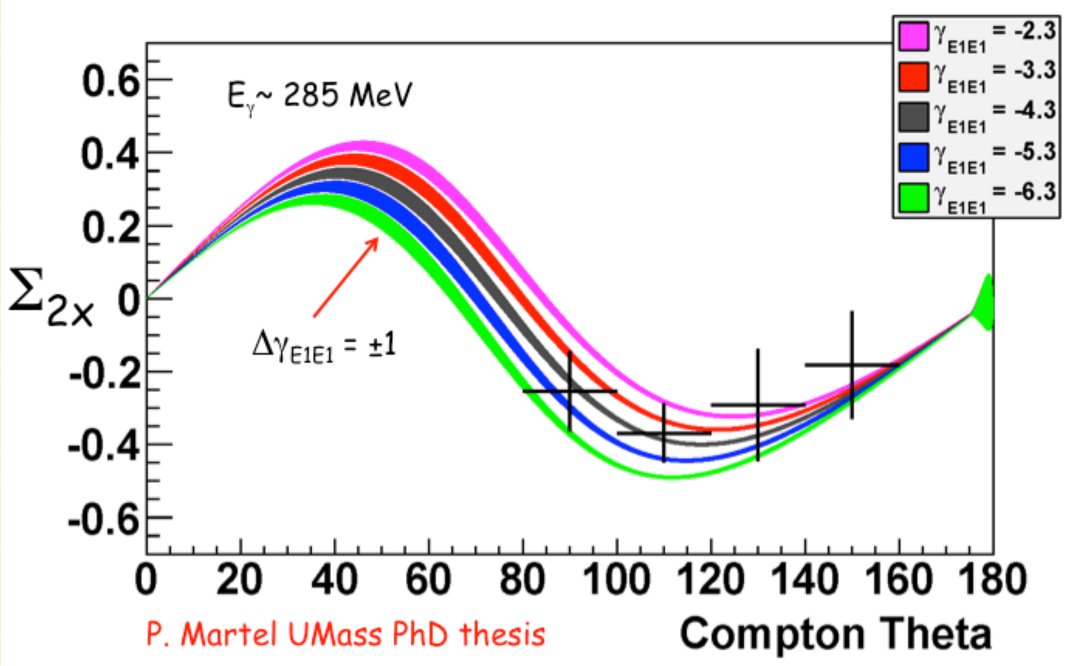
Picture credits: R. Miskimen

$$H = -2\pi[\gamma_{E1E1}\sigma\cdot(\mathbf{E}\times\dot{\mathbf{E}}) + \gamma_{M1M1}\sigma\cdot(\mathbf{B}\times\dot{\mathbf{B}}) - 2\gamma_{M1E2}\sigma_i B_j E_{ij} + 2\gamma_{E1M2}\sigma_i E_j B_{ij} + \ldots]$$

- Response of degrees of freedom that carry nucleon spin to E and B fields
- LQCD results in progress→TIBURZI







	χEFT	Fixed-t DR	Experiment
E1 E1	−1.1±1.8	−3.85±0.45	−3.5±0.12
M1 M1	2.2±0.5±0.7	2.8±0.1	3.16±0.85
E1 M2	−0.4±0.4	−0.15±0.15	−0.7±1.2
E2 M1	1.9±0.4	2.0±0.1	1.99±0.29

Spin polarizabilities, all in units of 10^{-4} fm^4

Future at MAMI: measurements of Σ_{2z}, Σ_3. Full multipole analysis of suite of Compton observables

Future at HIGS: low-energy

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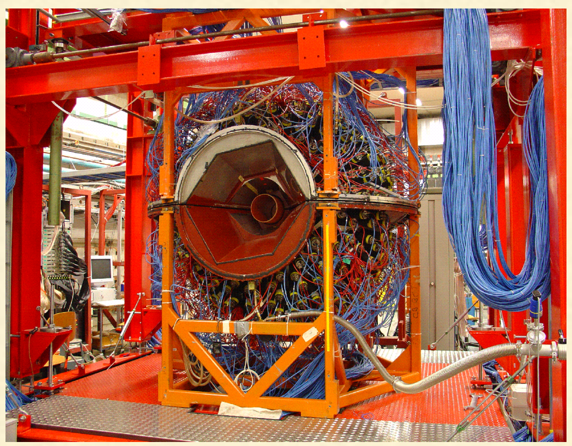

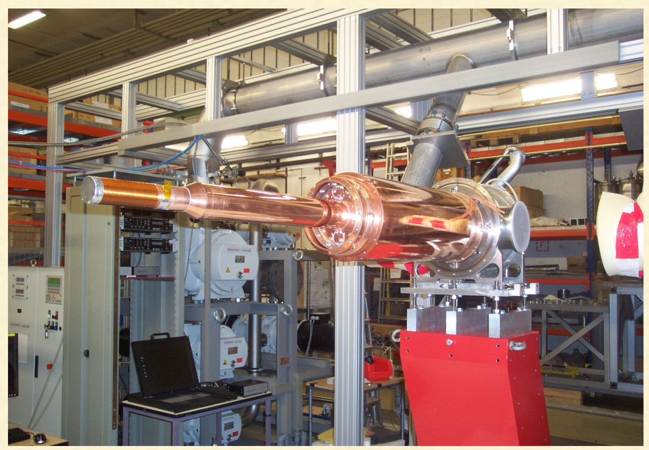

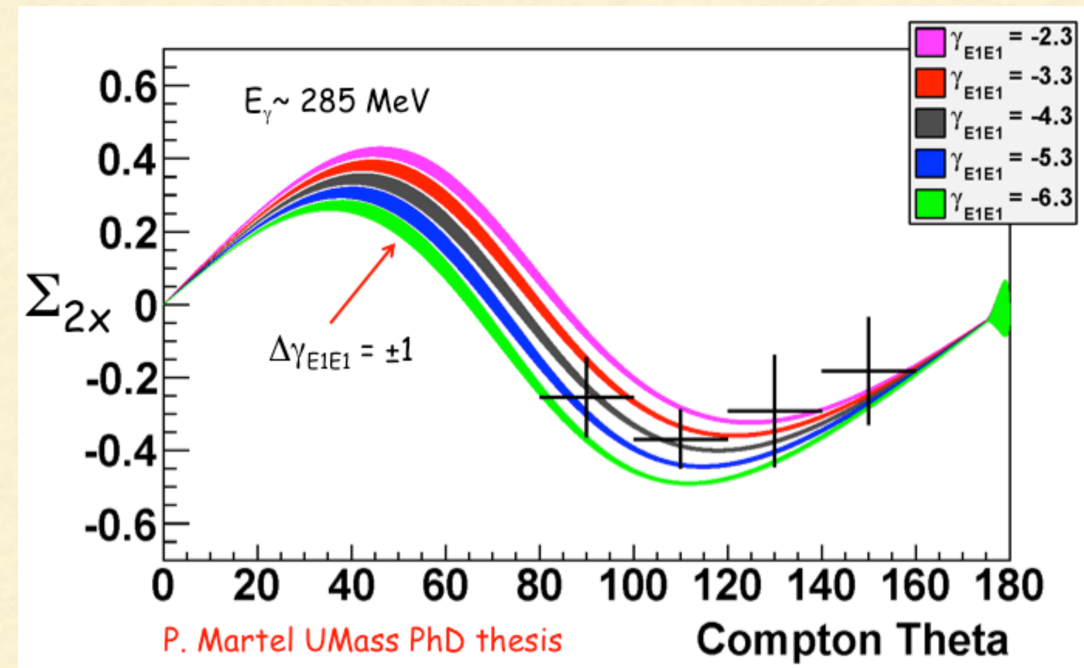

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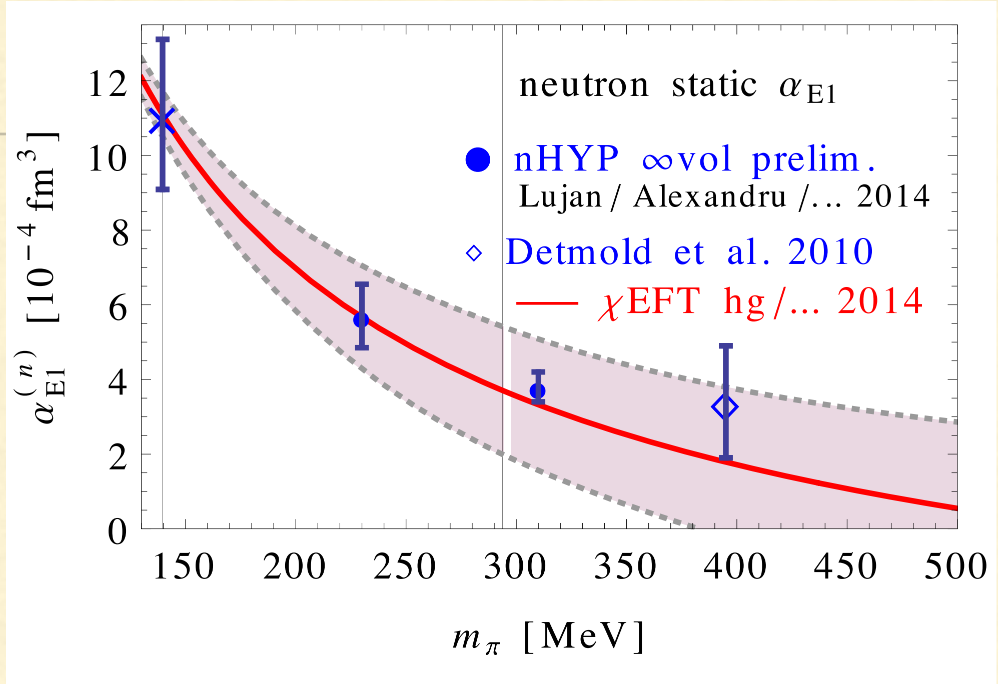
NEXT TALK

<u>Future at HIGS:</u> low-energy

FUTURE: A=1

Picture credits: A. Alexandru et al., Chiral MAID



MAMI, HIGS

Input for polarizability correction to extraction of r_p from μH

FUTURE: A=1

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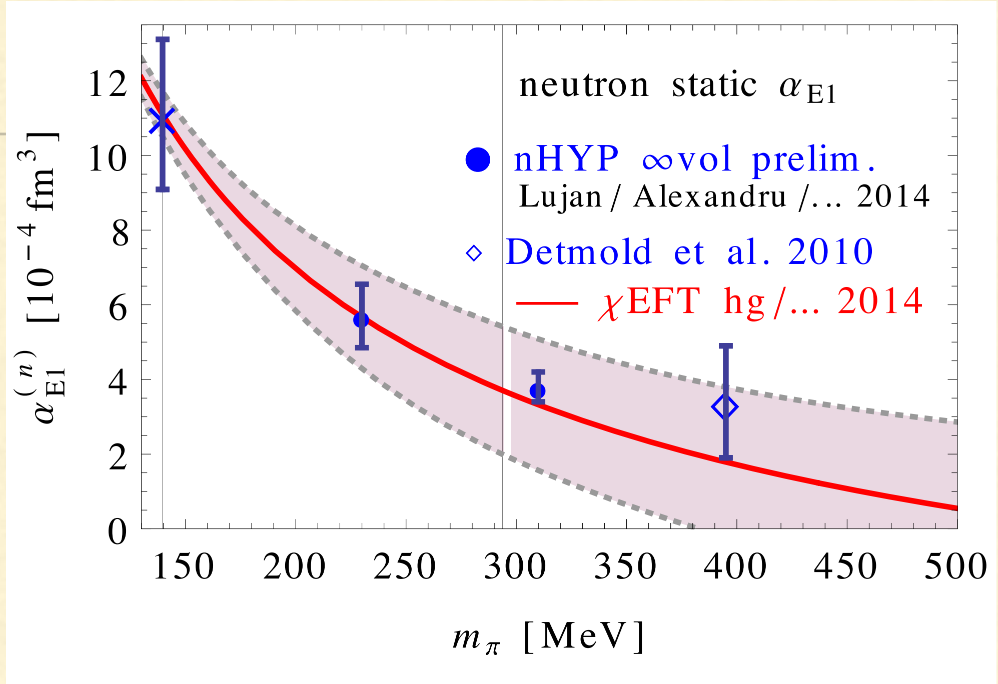

- Compton:
  - Lattice results: α, β, γs
  - First asymmetry data below 200 MeV
  - High-accuracy extraction of γ's

MAMI, HIGS

  - Resolution of high/low $\beta_{M1}^{(p)}$ issue via precision experiment and theory

    Input for polarizability correction to extraction of r_p from μH
  - Analyses of higher-energy data: combination of χPT and DR. Multipole analysis

    Role of 0^{++} exchange in t-channel
  - VCS is a largely unexplored frontier→probe spatial distribution of α, β, γs

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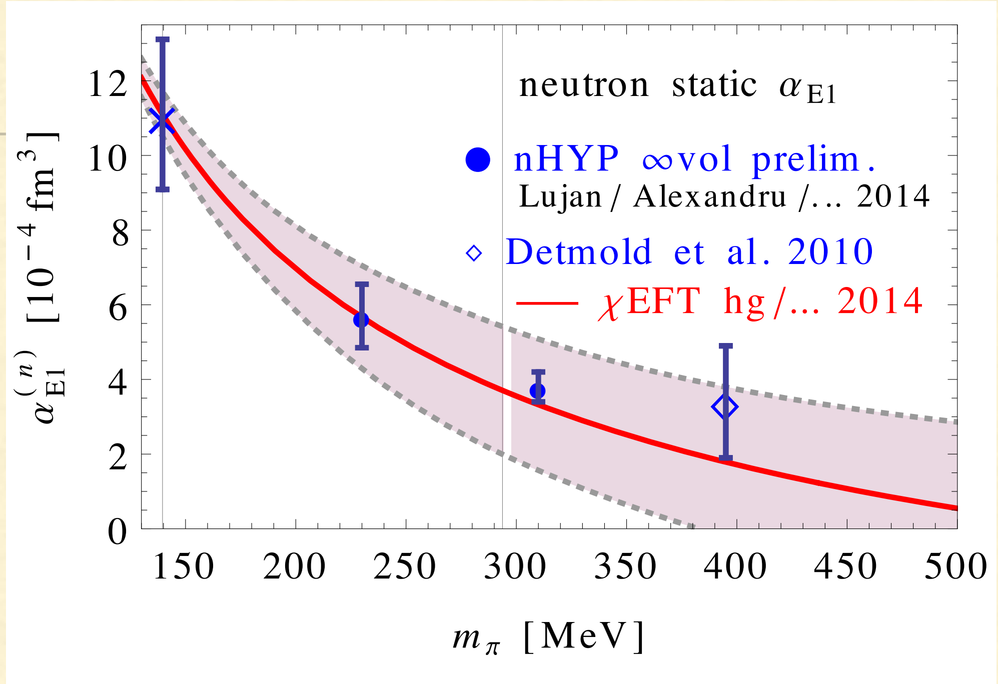

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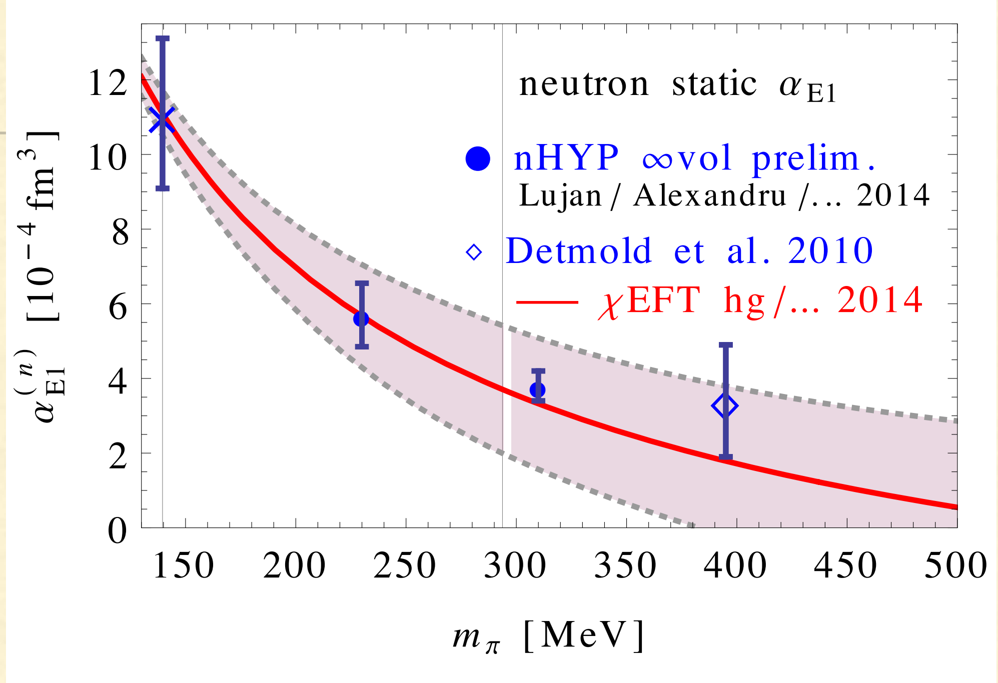
  - VCS is a largely unexplored frontier→probe spatial distribution of α, β, γs
- Pion photo- and electro-production
  - New results from MAMI (US involvement!); analysis of Hall A data in progress
  - Chiral MAID: need to add Δ(1232) d.o.f.

FUTURE: A=1

Picture credits: A. Alexandru et al., Chiral MAID



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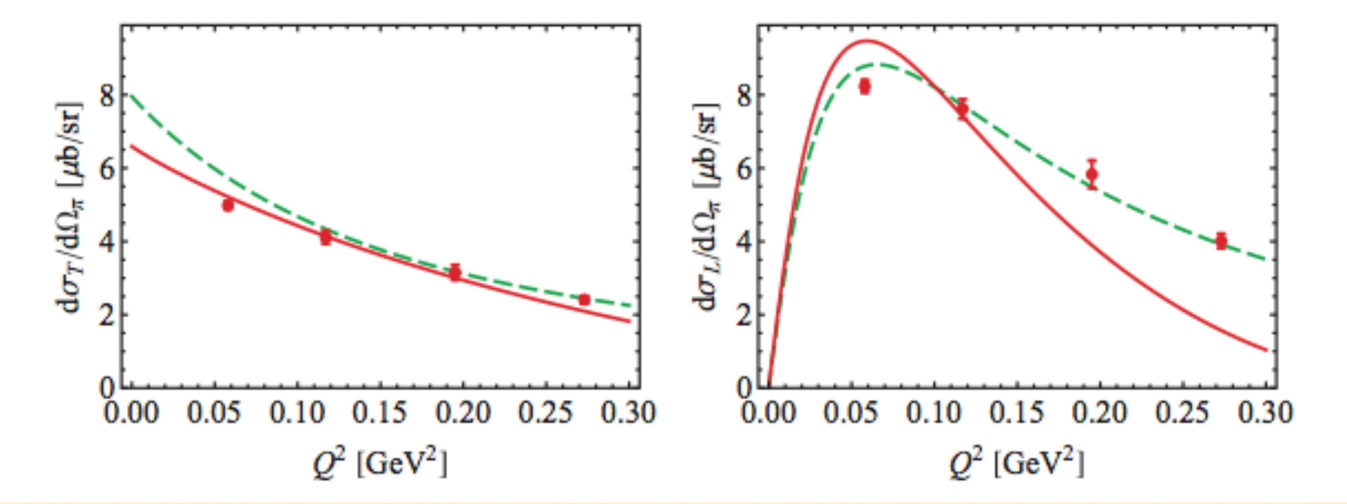
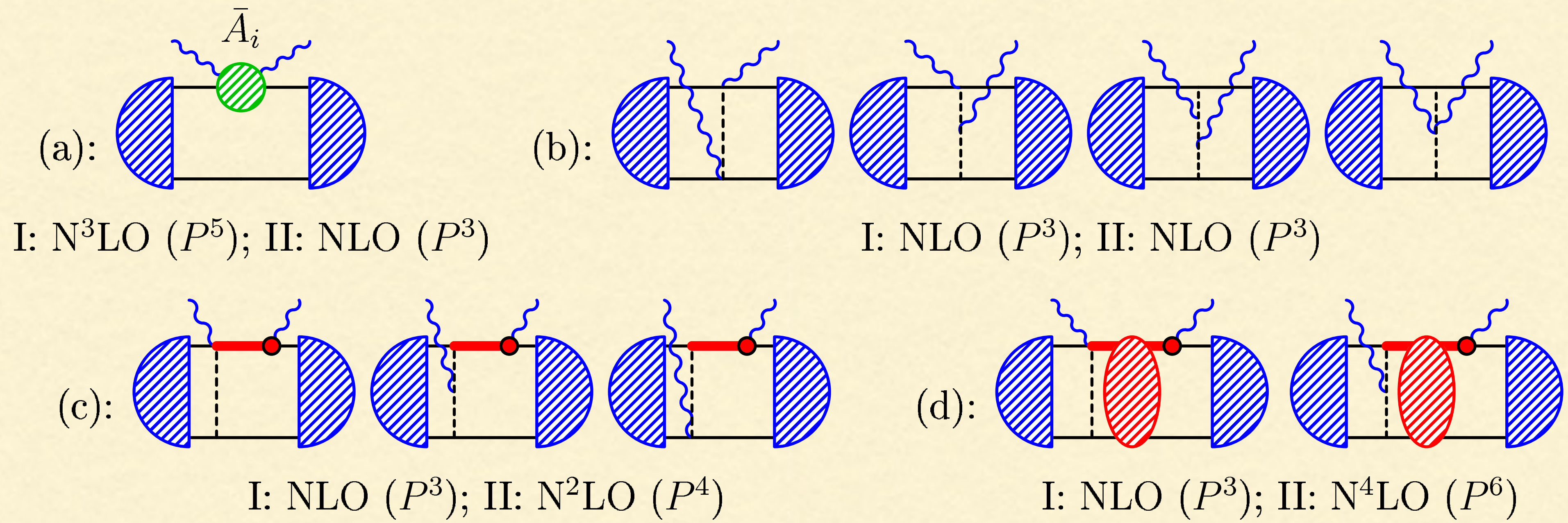
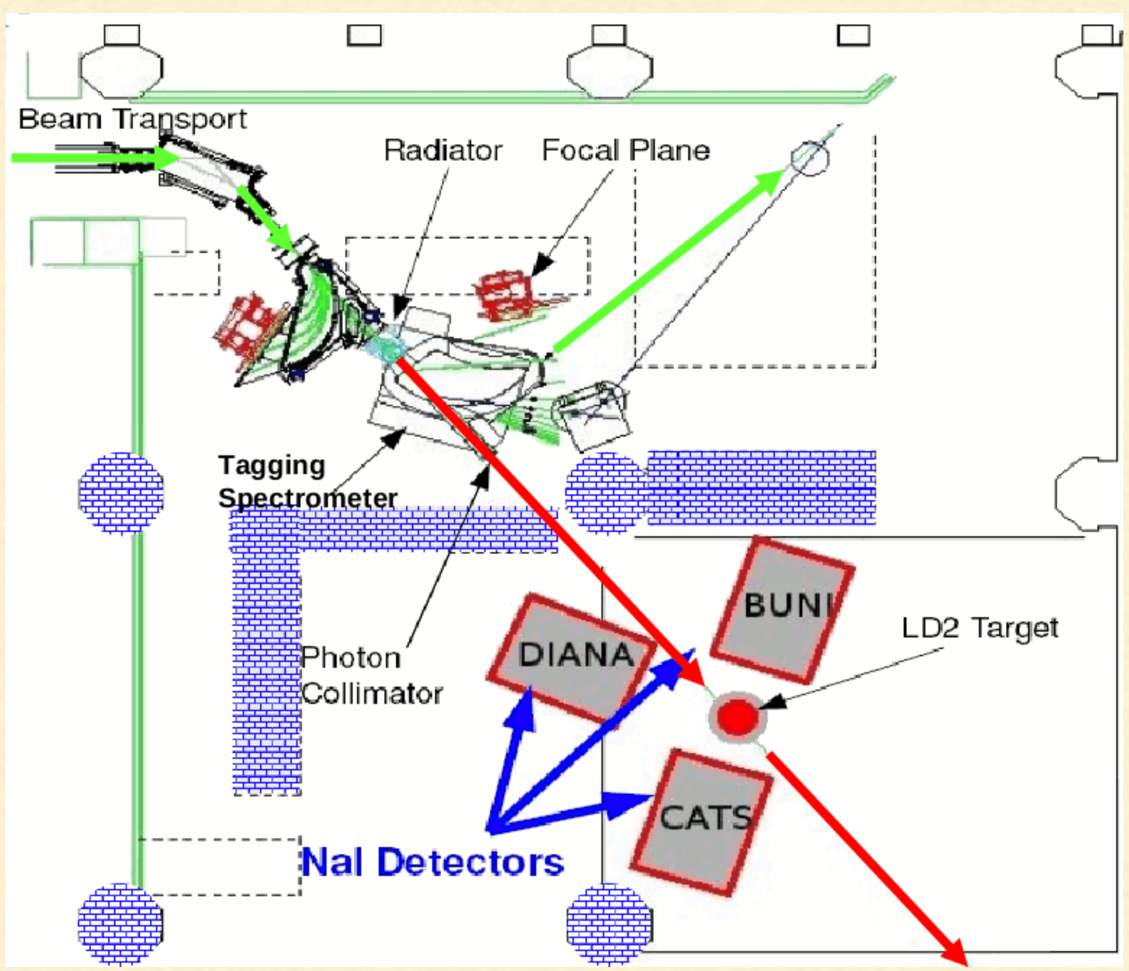
    Role of 0^{++} exchange in t-channel
  - VCS is a largely unexplored frontier → probe spatial distribution of α, β, γs
- Pion photo- and electro-production
  - New results from MAMI (US involven
  - Chiral MAID: need to add Δ(1232) d.



A=2: GETTING AT THE NEUTRON

Picture credits: H. Grießhammer, L. Myers



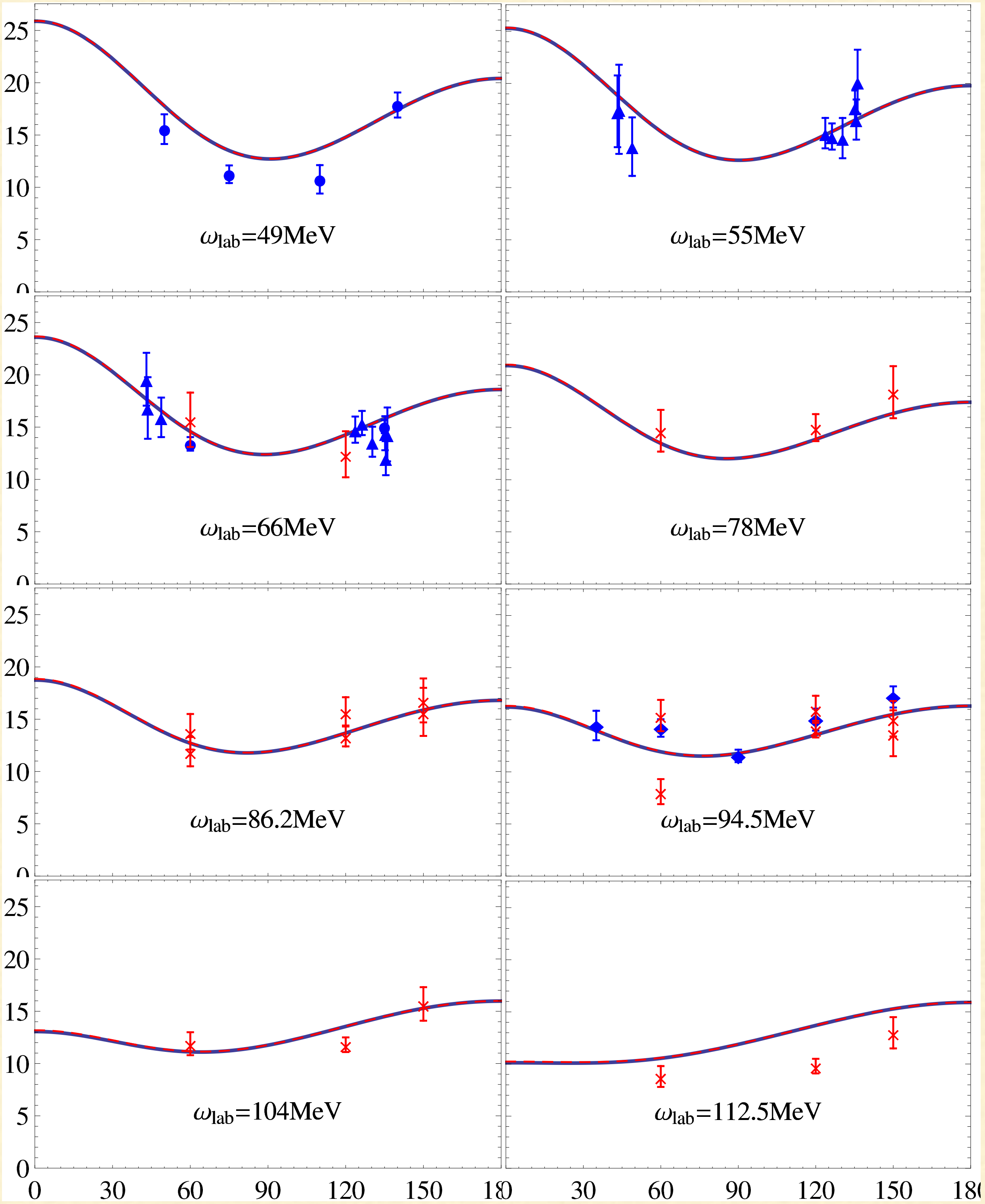


- Extract isoscalar combination of nucleon polarizabilities from elastic γd
- COMPTON@MAX-Lab collaboration: unification of γd expertise. Theory support.
- 15 years of development in χEFT: reached accuracy at or beyond experiment

→GRIESSHAMMER

COMPTON@MAXLAB

Picture credit: arXiv:1409.????



- U.S.-U.K.-Sweden collaboration
- Doubled world data-base

$$\alpha_n = 11.65 \pm 1.25(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \pm 0.8(\mathrm{th})$$
$$\beta_n = 3.55 \mp 1.25(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \mp 0.8(\mathrm{th})$$

- Hint of $\beta_n > \beta_p$? $\beta_n - \beta_p$ presently most uncertain input to $(M_p - M_n)^{em}$
- Higher-energy data being analyzed; theory for $E_\gamma > m_\pi$ under development
- Consistent with quasi-free $\gamma d \rightarrow \gamma np$
- Future QF: JLAB FEL for ARCS? Theory.
- Future: precision at lower energies; asymmetries $\rightarrow$ neutron γ's

COMPTON@MAXLAB

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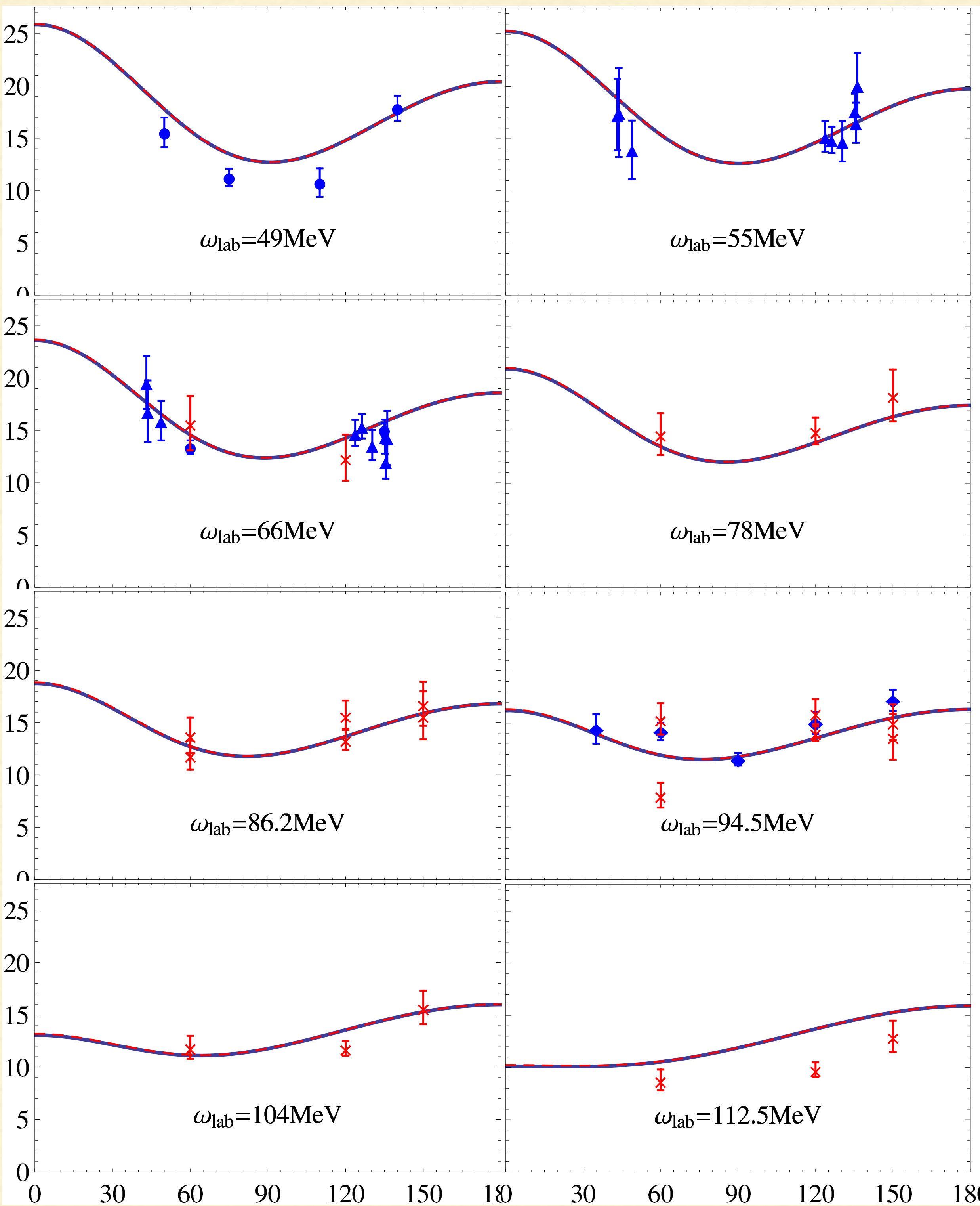

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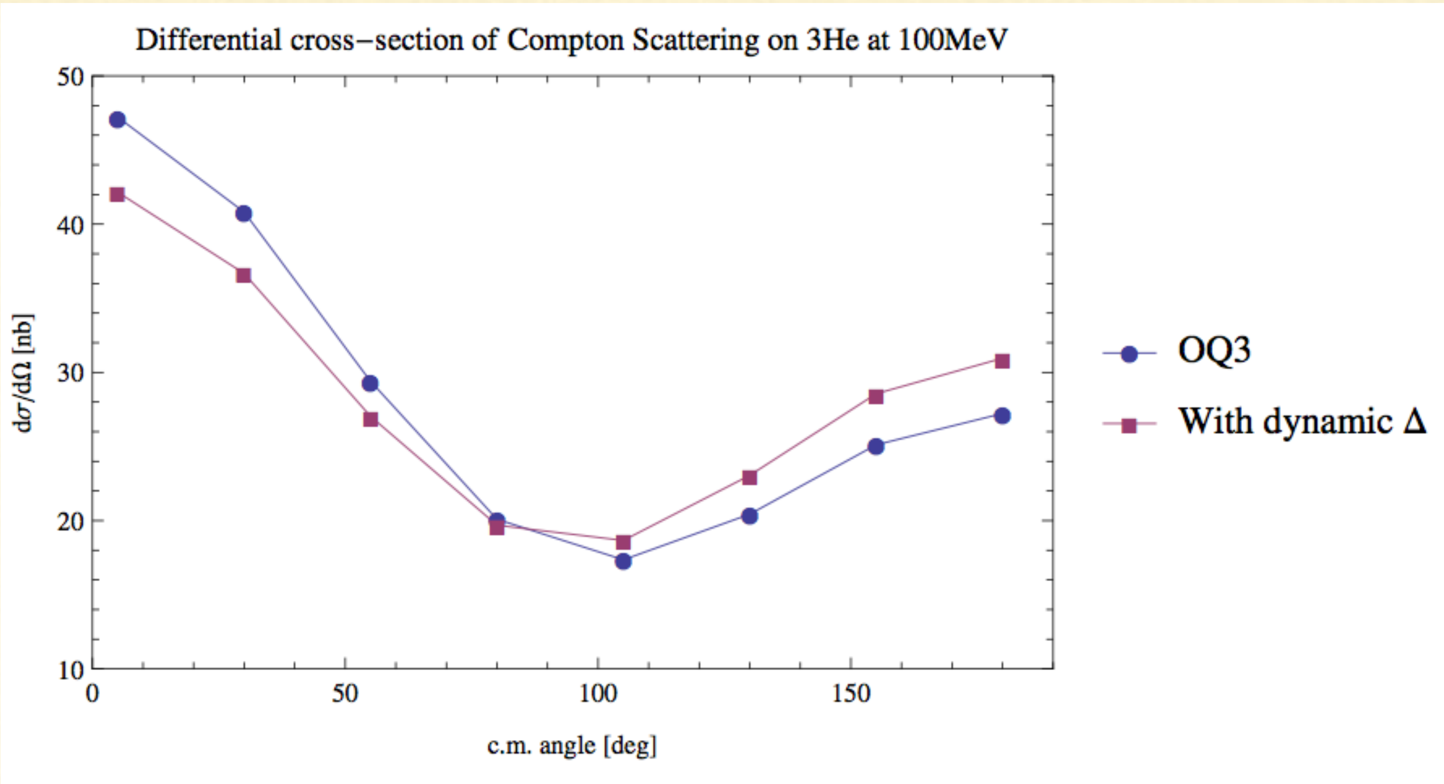
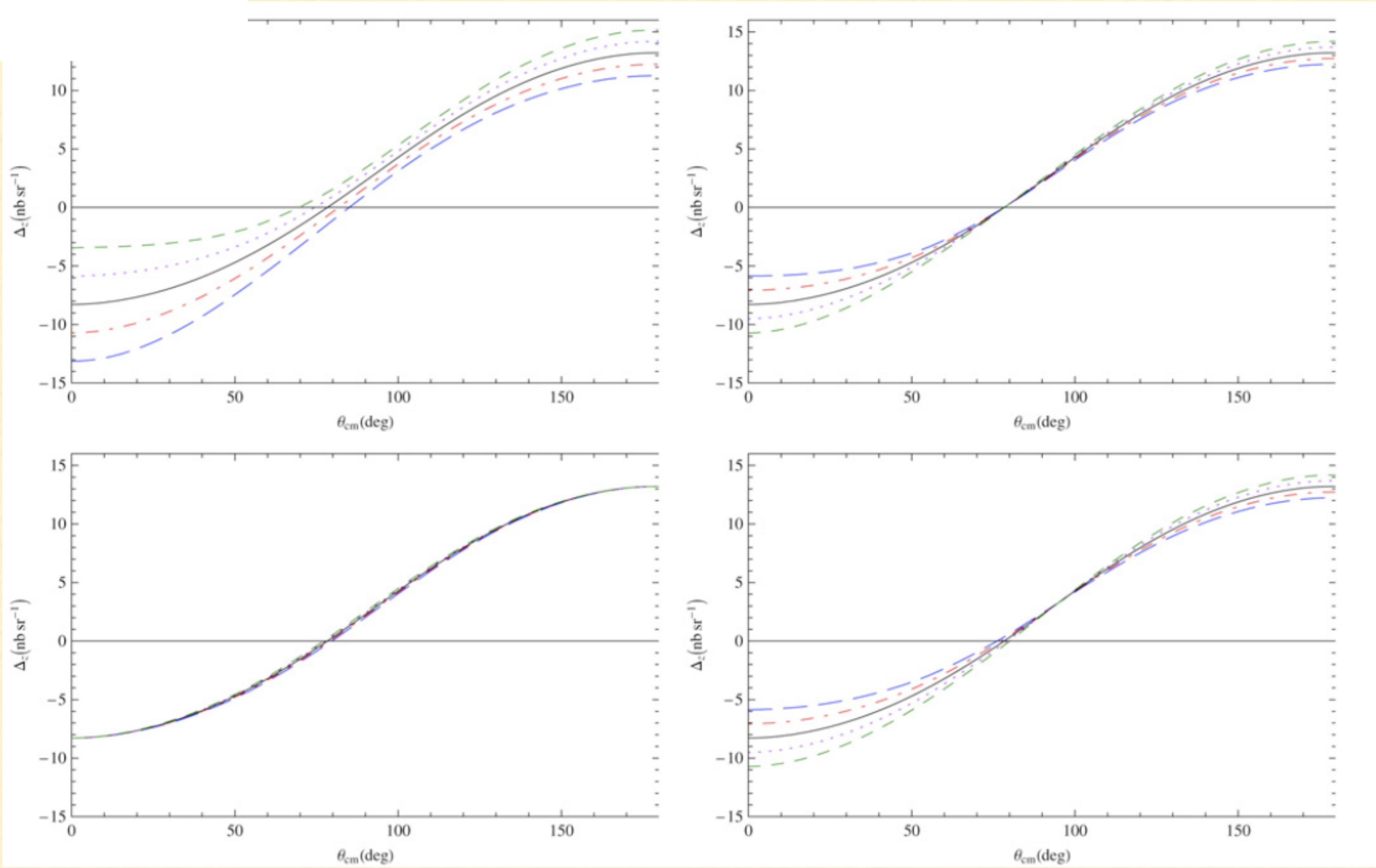
NEXT TALK

COMPTON IN A=3

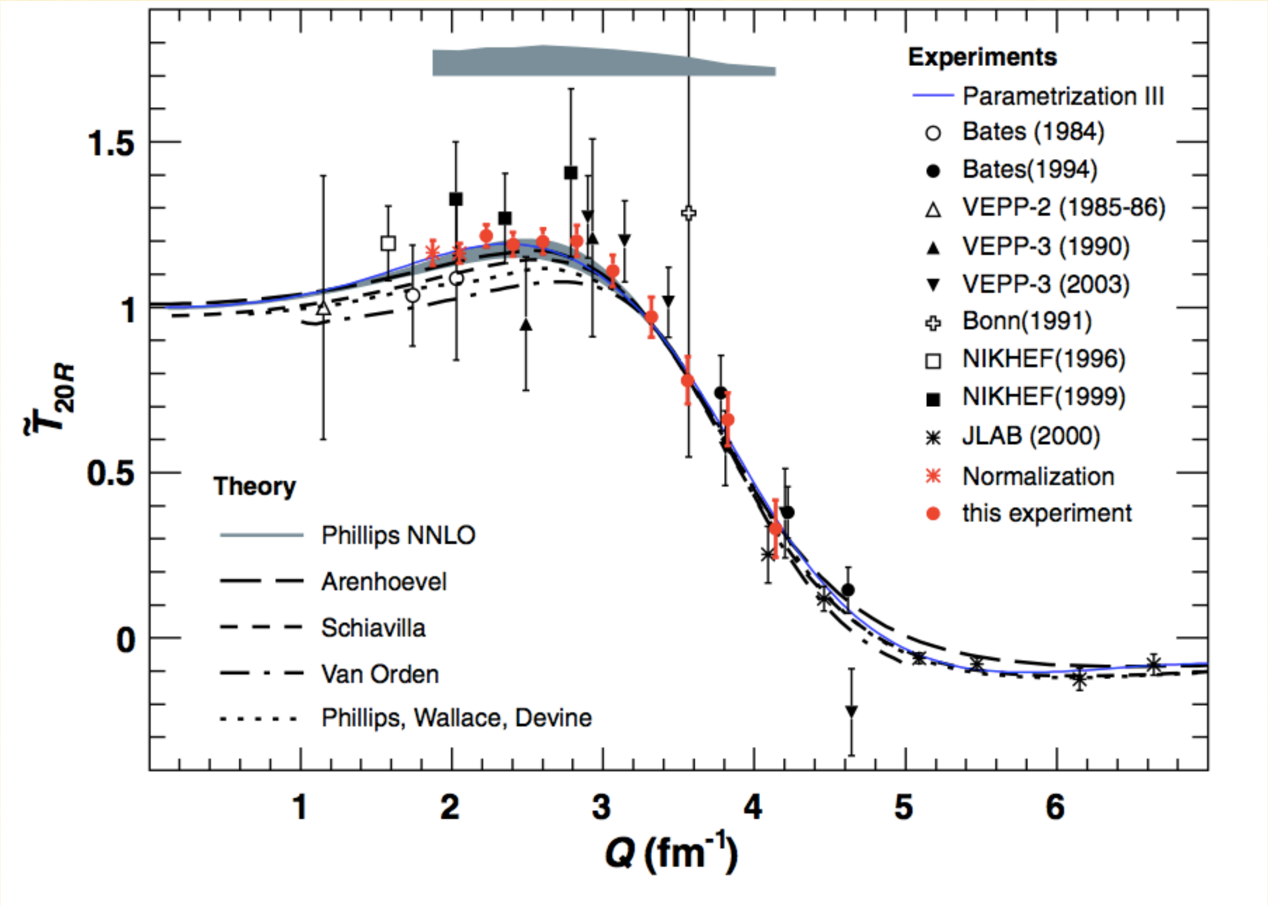


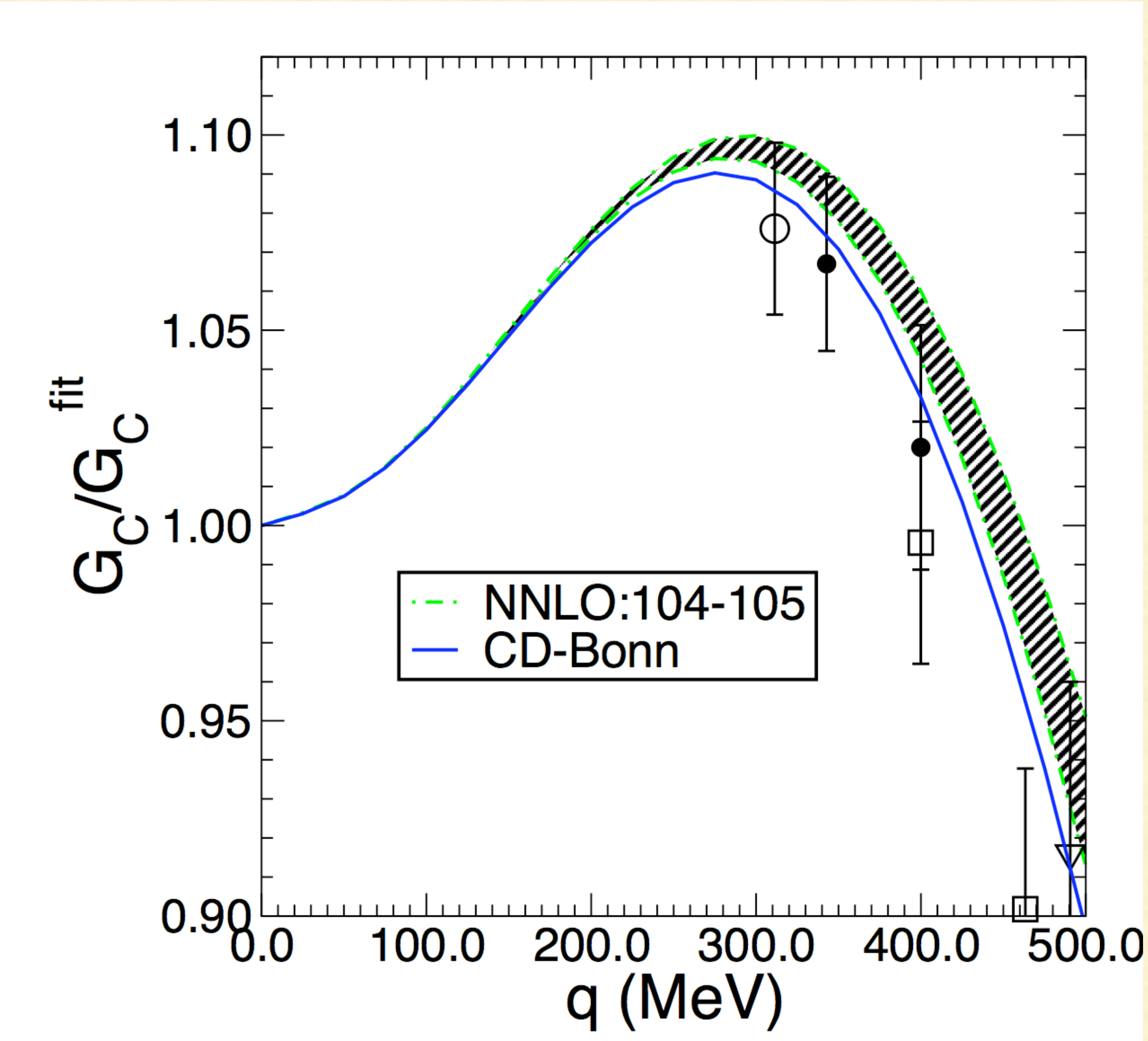
- Recent experimental interest in elastic Compton from ^{3}He, ^{4}He
- Larger charge⇒larger absolute effect of polarizabilities
- Theory: extension of γd

- HIGS: polarized ^{3}He target
- Asymmetries from polarized ^{3}He predicted to be as those from a free (polarized) neutron
- Access to neutron γs!



PRECISE EW STRUCTURE IN A=2





- Constrained to radius: 0.6% error bar in G_C/G_C^{fit} at Q=0.5 GeV/c

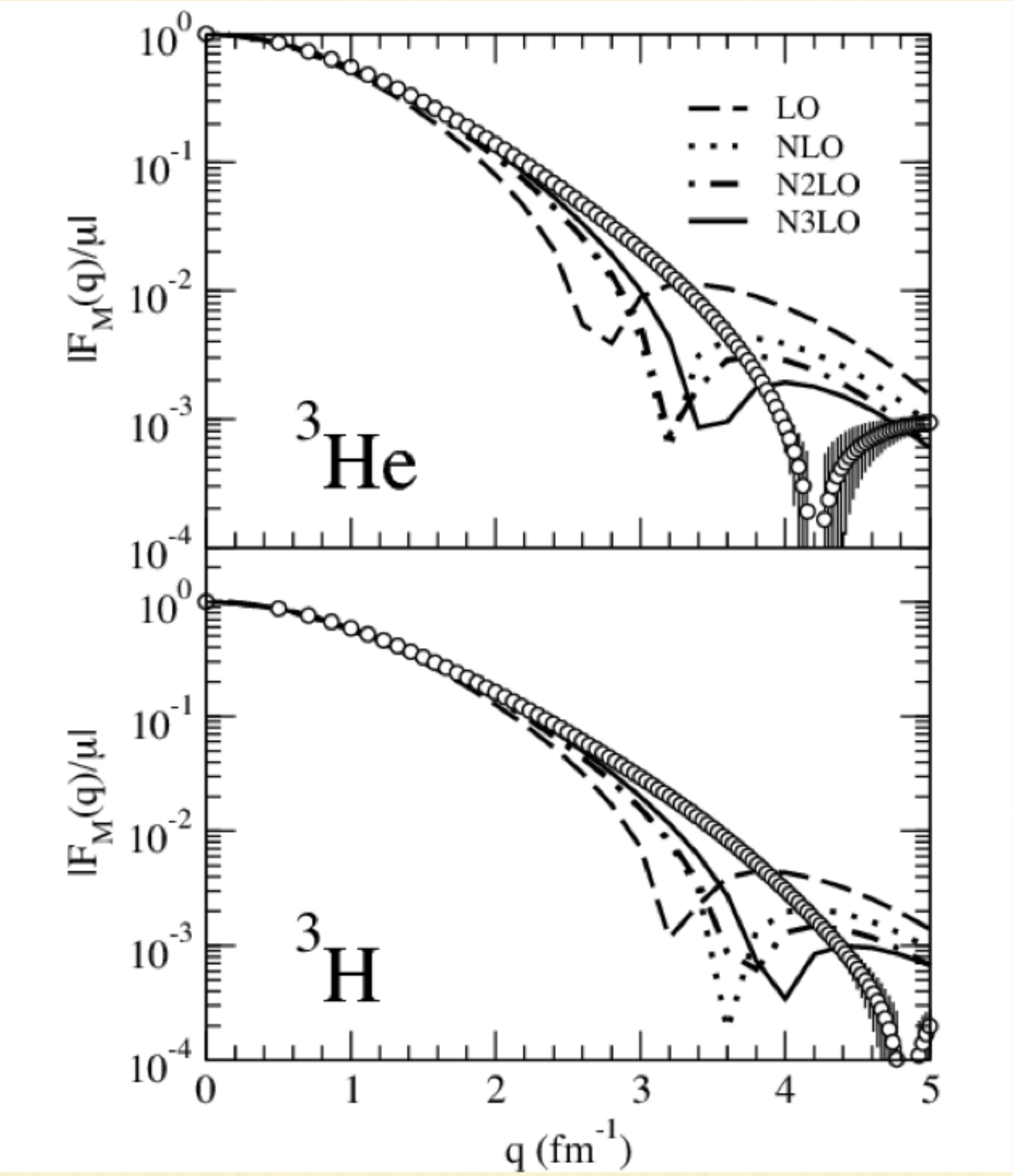
- Precision computation of polarizability corrections in μd: input to BSM search

$$\delta_{2\gamma E} = \delta^A_{\rm pol} + \delta_{\rm Zem} + \delta^N_{\rm pol} = 1.690 \pm 0.020 \text{ meV}$$

- Prediction for MuSun experiment: $\mu^- + d \rightarrow \nu_\mu + n + n; \Gamma_D = 393(3)\ \mathrm{s}^{-1}$

BEYOND A=3 AND THE FUTURE

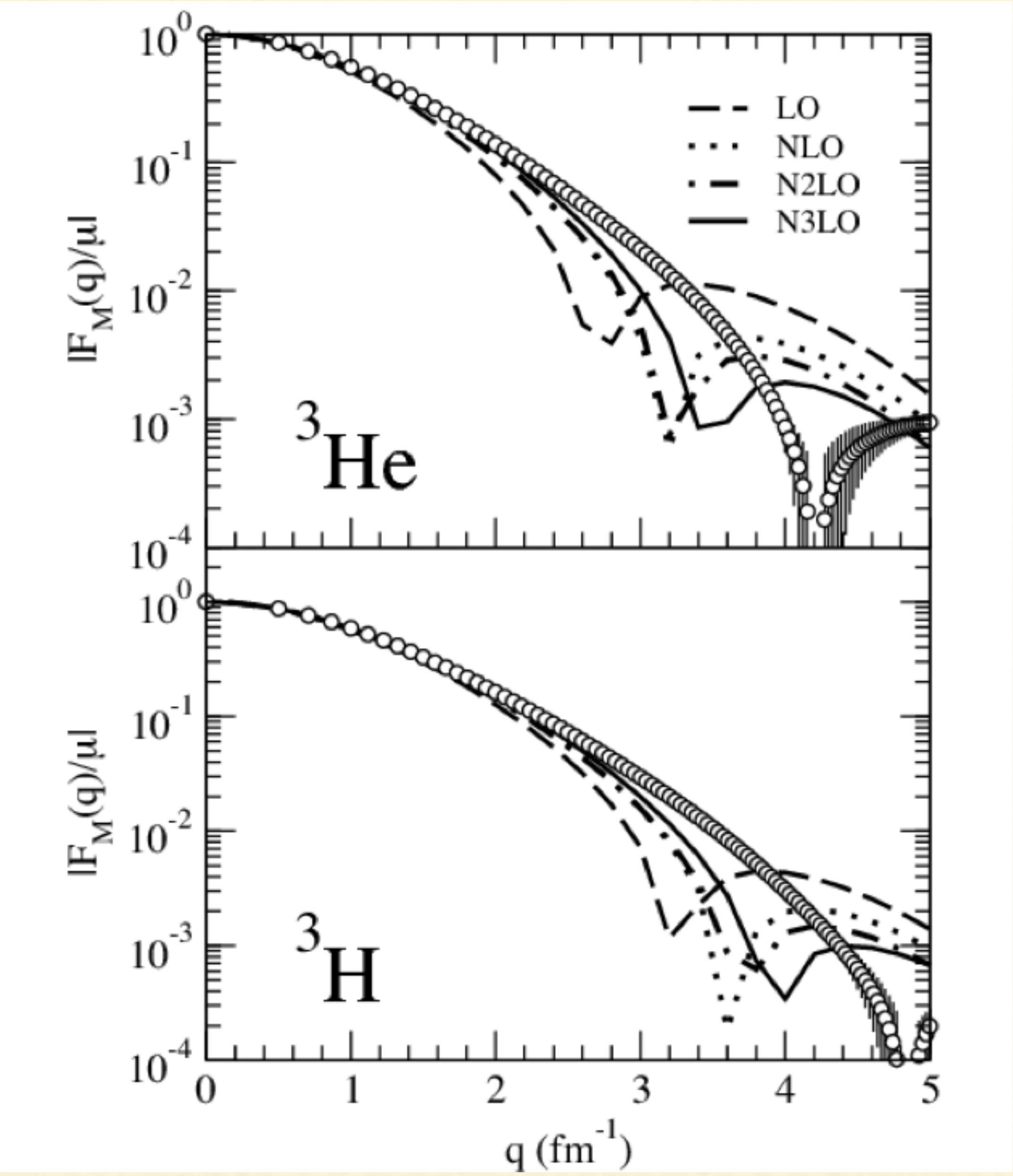
Picture credits: M. Piarulli et al., L. Myers et al., NPLQCD



BEYOND A=3 AND THE FUTURE

Picture credits: M. Piarulli et al., L. Myers et al., NPLQCD

- Analogous computation for μ^- capture on ^{3}He sets limits on BSM physics
- Confidence in ability of χEFT to describe few-body electroweak structure



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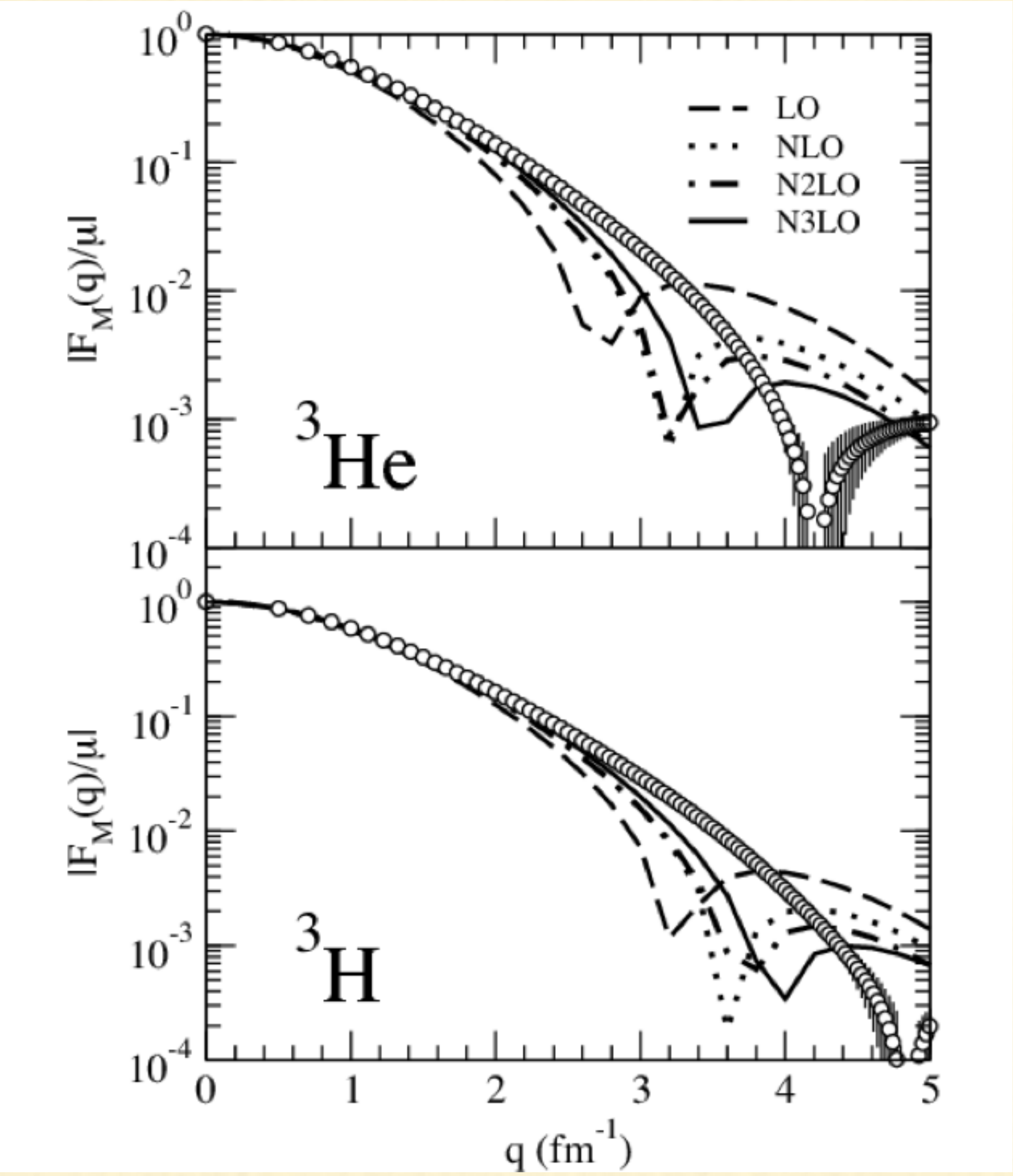
- Next seven years will see precise calculations of EM structure to at least A=12



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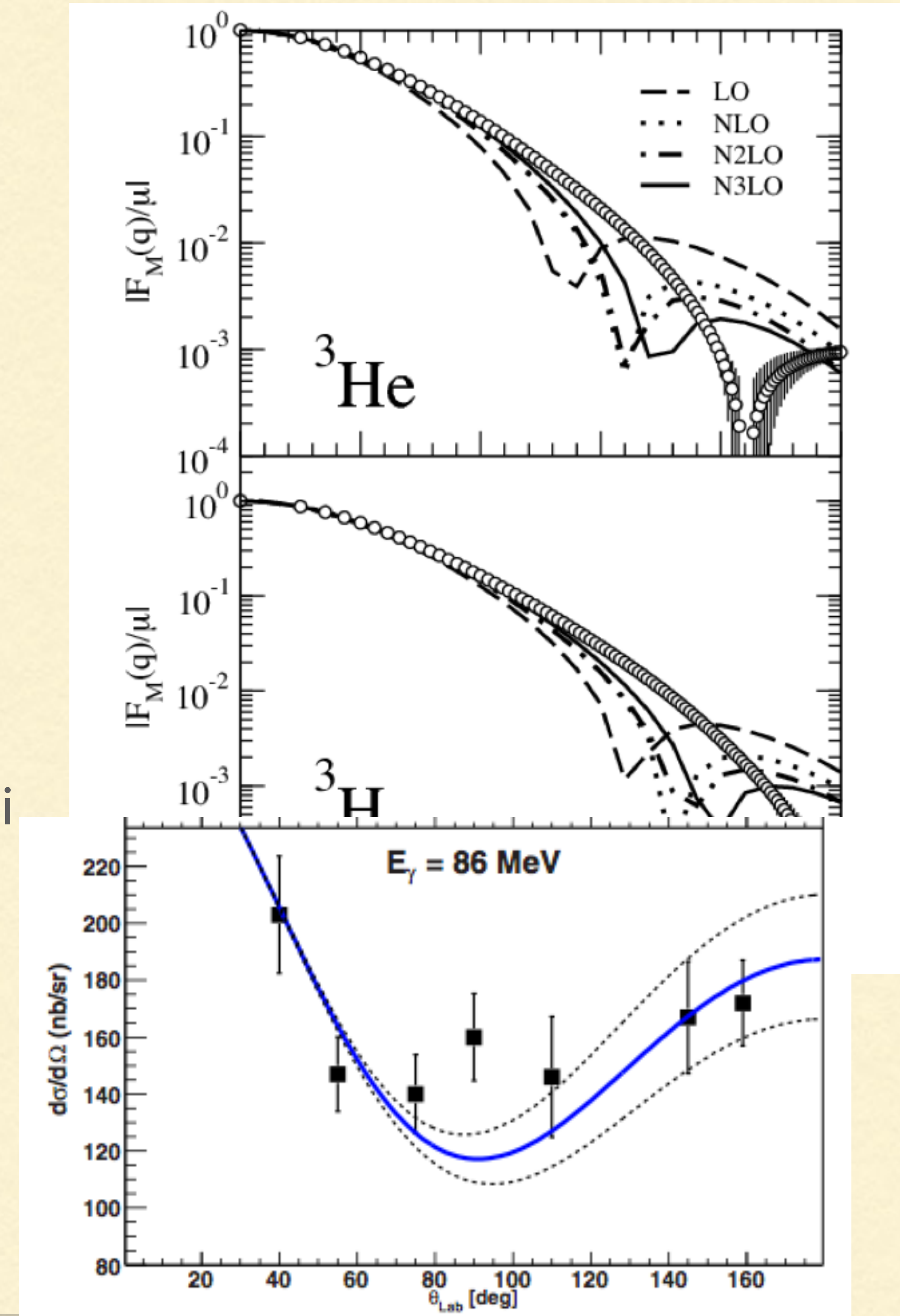

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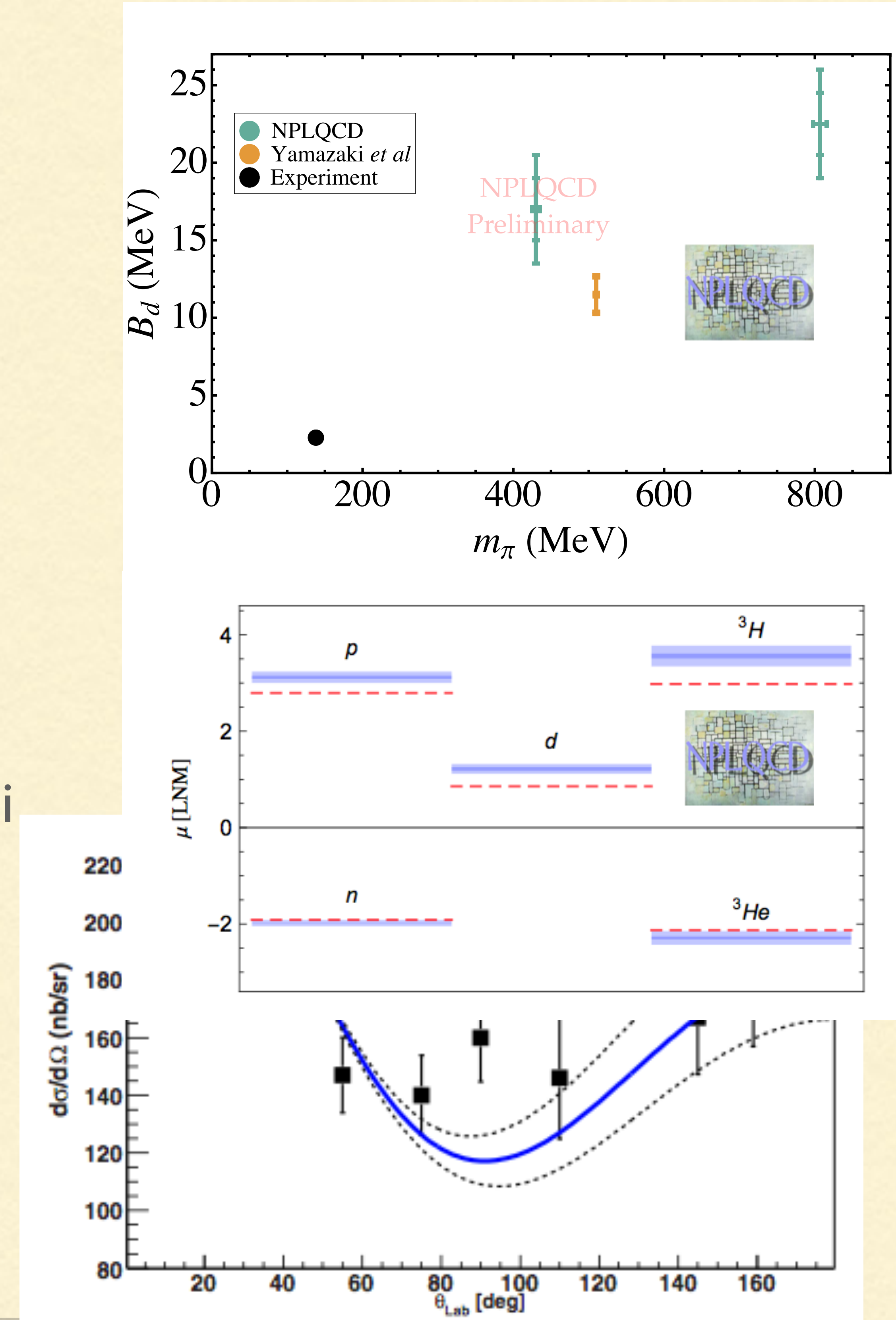
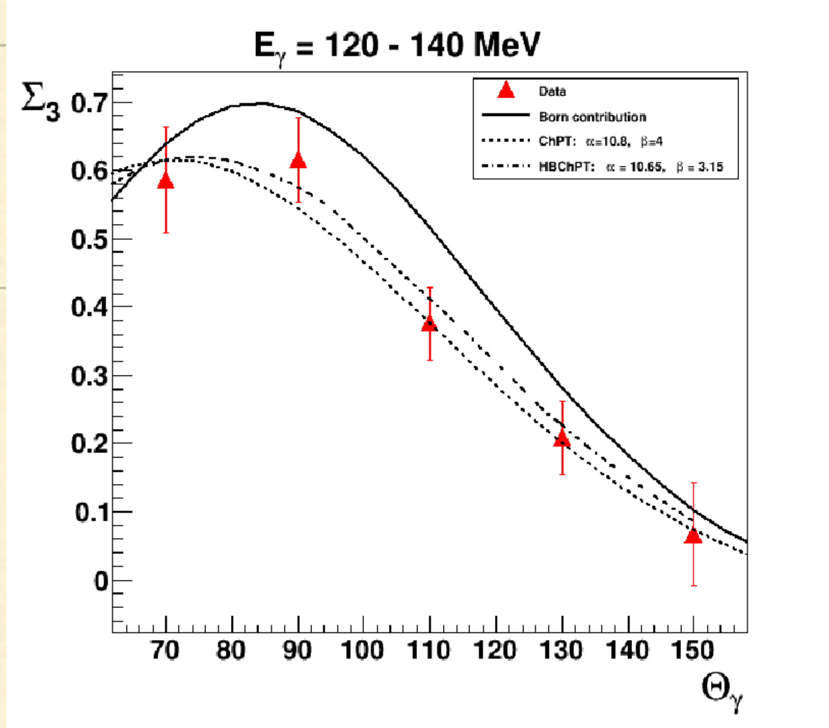
LQCD for nuclei ⟷ Laboratory measurements

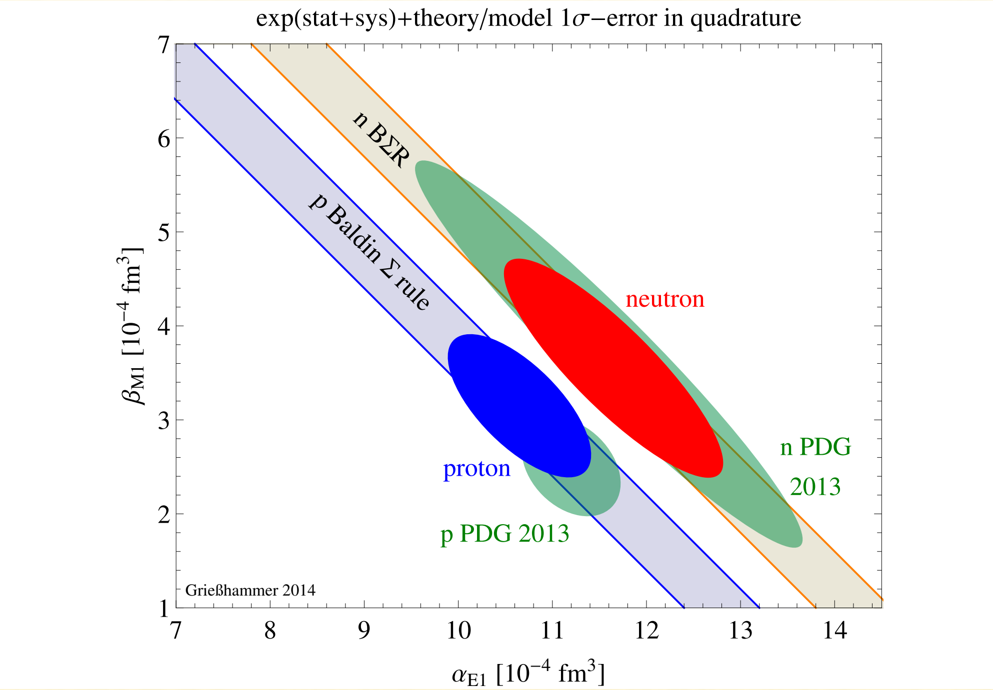
EFT

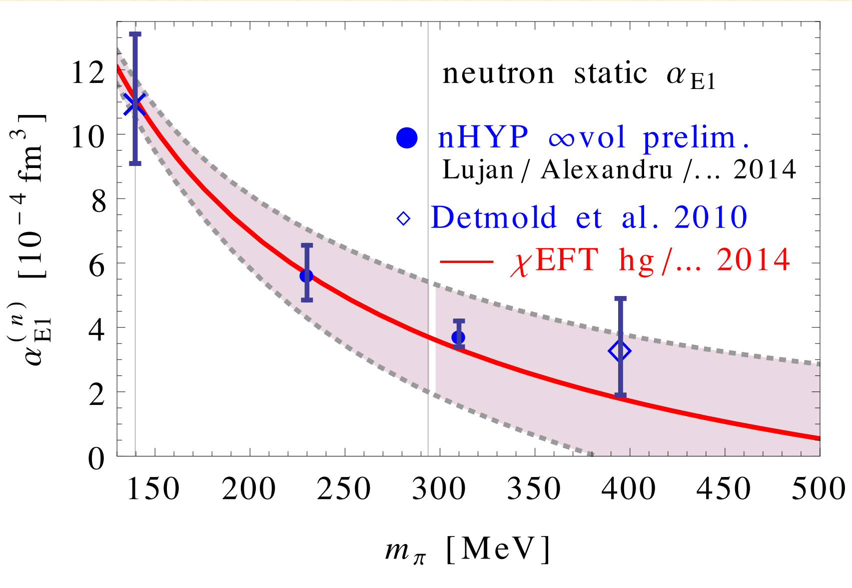


BROAD THEMES

Picture credits: E. Downie, H. Grießhammer, A. Alexandru et al.







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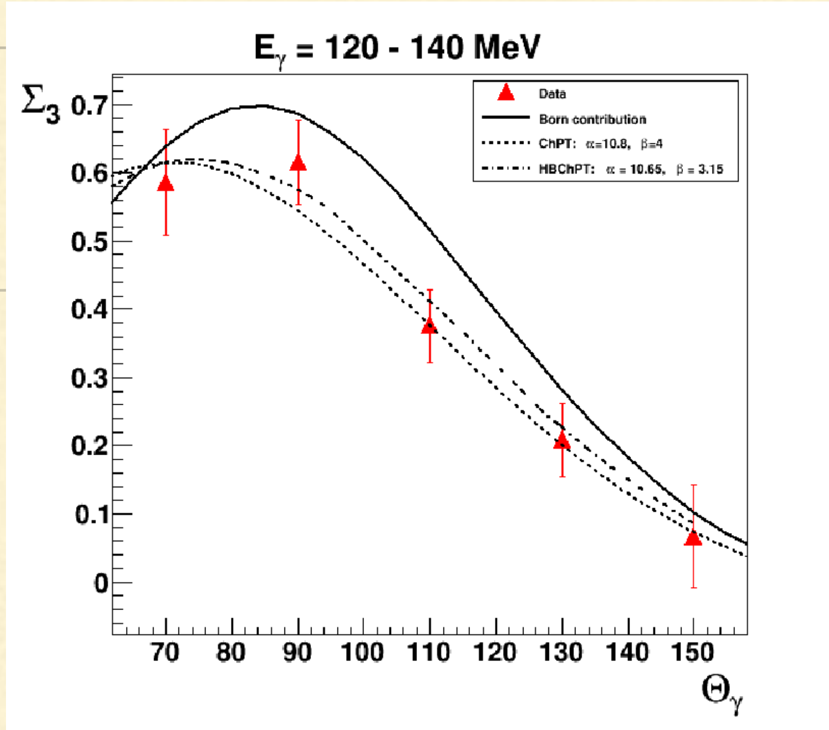
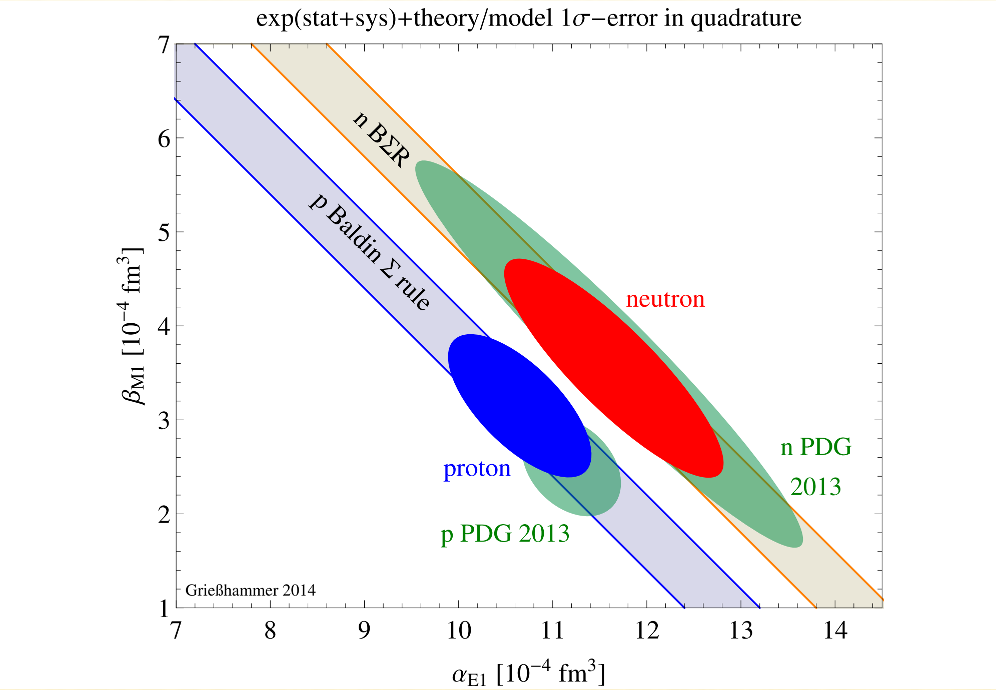
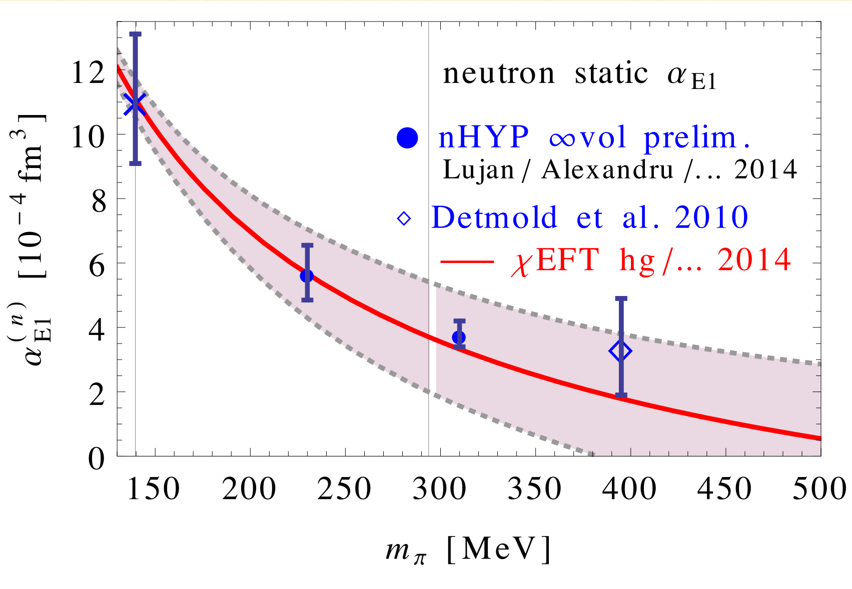
- Theory: synergistic blend of LQCD, EFT, phenomenology
- Understand QCD interplay of π, Δ, heavier d.o.f.
- Strong emphasis on uncertainty quantification
- New experimental facilities and capabilities provide new opportunities to observe this interplay







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- Understand QCD interplay of π, Δ, heavier d.o.f.
- Strong emphasis on uncertainty quantification
- New experimental facilities and capabilities provide new opportunities to observe this interplay
- Theorists and experimentalists working together to identify best opportunities and interpret data
- Improvement in understanding of nuclear dynamics from χEFT (and ultimately LQCD) allows nuclei to be used as neutron targets in novel ways.
- Chiral dynamics in A=0, 1, 2, …now a precision tool: particularly important for BSM-physics searches